THE DESIGN, CONSTRUCTION, AND OPERATION OF A CARBON DIOXIDE ABSORPTION TOWER

A THESIS

Submitted in partial fulfillment
of the requirements for the Degree
of Master of Science in Chemical Engineering

by

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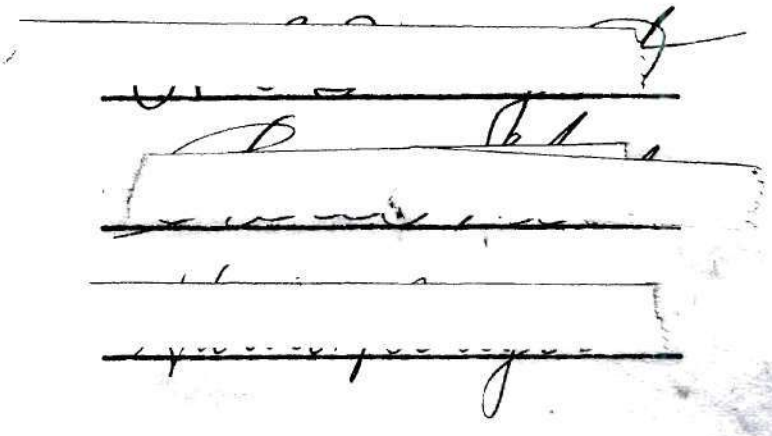
APPROVED



May 1938

TABLE OF CONTENTS

ACKNOWLEDGMENT

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FOREWORD

The purpose of this work was to design and construct a carbon dioxide absorption tower which could be located in the Chemical Engineering laboratory and which would be suitable to illustrate the absorption as a unit operation. As far as possible all the fabrication was done in the shop of the Chemical Engineering laboratory. As a result, some of the units in the equipment are not as elaborate as they might be. The only criterion considered in its construction was that it should function well enough to accomplish its purpose.

INTRODUCTION

The history (1) of carbon dioxide itself dates back to the seventeenth century when it was first recognized by J. B. van Helmont as a separate gas, distinct from other gaseous substances in its chemical and physical properties. While his findings were published, nothing of importance industrially developed until Faraday liquified the gas in 1823. This accomplishment marked the beginning of a more extensive investigation of the properties of carbon dioxide, and in 1835 Thelorier produced solid carbon dioxide for the first time.

Up until 1889 all of the carbon dioxide came either from natural sources such as springs, wells and caves, or was obtained by the action of an acid on a carbonate. In this year the Kolensaure-Werk in Erkner, near Berlin, started producing carbon dioxide by the absorption process; the actual beginning of the modern industry, and the method which is being used at the present time.

The production of carbon dioxide by the absorption process is accomplished by producing either intentionally or as a by-product, a gaseous mixture containing from 10 to 20 per cent carbon dioxide. About three-fourths of this carbon dioxide is recovered by absorbing it in an alkaline medium. The absorbed carbon dioxide is subsequently recovered in a

(1) Quinn, E. L., and Jones, C. L., "Carbon Dioxide", p. 11, The Reinhold Publishing Corp., 1936.

pure state and compressed and sold either as a gas, a liquid, or a solid for various purposes. (2) The gas mixtures from which carbon dioxide is obtained are flue gases, motor exhaust gases, kiln gases and waste gases from the Haber Ammonia process.

The absorption equipment to be dealt with in this work used a sodium carbonate solution as the absorption medium. The gas was passed upward through a coke packed tower countercurrent to the sodium carbonate solution. The carbon dioxide reacts with the sodium carbonate in the following manner:

$$CO_2 + Na_2CO_3 + H_2O \rightleftharpoons 2\ NaHCO_3$$

This reaction is reversible and the carbon dioxide is recovered simply by boiling the sodium bicarbonate solution. This again forms the sodium carbonate solution which is then recycled.

(2) Jones, C. L., Chem. and Met. Eng., 40, 76-9 (1933).

PART I - THEORY OF GAS ABSORPTION

In order to transfer a soluble gas from the gas mixture to the liquid, it must diffuse through the surface existing between the liquid and the gas phases. This surface consists of the gas film, the interface between the two phases, and a liquid film. (3) It is reasonable to assume that equilibrium is reached at the interface; that is to say, the partial pressure exerted by the active component or soluble gas at an infinitesimal distance above the interface is equal to the pressure exerted by the same component which is dissolved in the liquid, and which is at an infinitesimal distance below the interface. This partial pressure, or its equivalent, shall be designated as y_i , and the concentration of the active component dissolved in the liquid and at an infinitesimal distance below the interface shall be designated as x_i. If y, the partial pressure of the active component in the gas mixture is greater than y_i , then the active component will diffuse through the gas film toward the interface and a measure of the force driving the active component through the gas film is the difference $(y - y_i)$.(4) Likewise, if the concentration of the active component in the liquid, x, is less than the concentration at the interface, x_i, this component will diffuse through the liquid film in a direction away from the interface, and a measure of the driving force is the difference $(x_i - x)$.

(3) Whitman, Chem. and Met. Eng., 29, 147 (1923).
(4) Colburn, Ind. and Eng. Chem., 22, 967 - 970 (1930).

Setting up an expression for the rate of transfer through each film gives the equation

$$w = k_g A(y - y_i) = k_L A(x_i - x) \qquad (I)$$

where w = lbs. of solute gas transferred/hr.

k_g = gas film coefficient in $\frac{\text{lb. solute transferred thru film}}{(\text{sq.ft.})(\text{hr})\frac{\text{lb. solute}}{\text{lb. solvent}}}$

A = surface area where absorption is occuring in sq.ft.

y = lbs. solute gas/lb. inert gas in gas phase

y_i = lbs. solute gas/lb. inert gas at the interface

k_L = lq. film coeff. in $\frac{\text{lb. solute transferred thru film}}{(\text{sq.ft.})(\text{hr})\ \frac{\text{lb. solute}}{\text{lb. solvent}}}$

x_i = the concentration of the solute gas at the interface in $\frac{\text{lb. solute}}{\text{lb. solvent}}$

x = the concentration of the solute gas in the main body of the liquid in $\frac{\text{lb. solute}}{\text{lb. solvent}}$.

If the gas is a slightly soluble one, the liquid film is controlling (5) and the resistance in the gas film is negligible compared to that in the liquid film and may be considered equal to K_L, the overall coefficient. Then Equation (I) may be written

$$w = K_L A(x_i - x) \qquad (II)$$

where $K_L = \frac{\text{lbs. solute transferred}}{(\text{sq.ft.})(\text{hr})\ \frac{\text{lb. solute gas}}{\text{lb. inert gas}}}$.

Now considering a continuous counter-current absorption tower of the packed type as shown diagrammatically in Fig. I,

(5) Walker, Lewis & McAdams, "Prin. Chem. Eng.", p.656, McGraw-Hill, 1927.

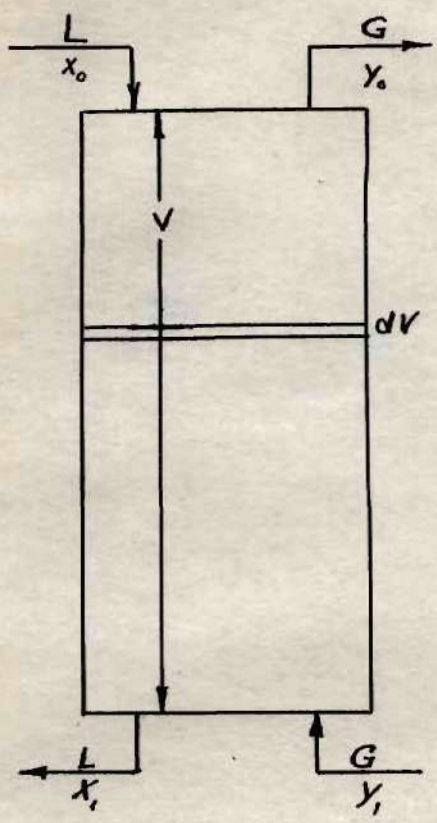


Figure I

and if

L = lbs. of absorbing liquid/hr.

G = lbs. of inert gas/hr.

y = lbs. of solute gas/lbs. of inert gas

x = lbs. of solute gas/lb. of absorbing liquid

V = volume of tower in cu. ft.

a = effective absorption area in sq. ft./cu. ft. packing

then a material balance may be set up:

$$Gdy = Ldx = dw \qquad \text{(III)}$$

and since A = aV, Eq. (II) becomes

$$dw = K_L (x_i - x)\, a\, dV \qquad \text{(IV)}$$

and

$$Ldx = K_L a (x_i - x)\, dV \qquad \text{(V)}$$

Separation of the variables and integration gives

$$\int_{x_o}^{x_1} \frac{dx}{x_i - x} = \frac{K_L a}{L} \int_o^V dV = \frac{K_L a}{L} V \qquad \text{(VI)}$$

$K_L a$ is given as one value expressed in $\frac{\text{pounds transferred}}{(\text{cu. ft.})(\text{hr})\frac{\text{lbs. solute gas}}{\text{lbs. absorbing lq.}}}$

and has to be determined experimentally. The value of $\int_{x_o}^{x} \frac{dx}{x_i - x}$ is obtained by a graphical integration, where $\frac{1}{x_i - x}$ is plotted against x.

In order to determine the driving force $(x_i - x)$, the operating line must be located on the equilibrium diagram which

is a plot of y against x. The equation of the operating line is obtained from Eq. (III) by a simple integration, using the terminal conditions of the absorption tower, Fig. I:

$$G\int_{y_o}^{y_1} dy = L\int_{x_o}^{x_1} dx$$

$$G(y_1 - y_o) = L(x_1 - x_o) \qquad \text{(VII)}$$

Then the operating line can be plotted and the value of $x_1 - x$ obtained for various values of x, and the term $\int_{x}^{x_1} \frac{dx}{x_1 - x}$ is evaluated.

PART II - THE DESIGN OF A CO_2 ABSORPTION TOWER

Inasmuch as this equipment was to be designed for use in the Chemical Engineering laboratory, its physical size was limited by the height of the laboratory. Therefore, a suitable size was selected and its capacity calculated. This is the reverse of the usual process for designing absorption equipment. The overall height of the laboratory was slightly over 20 ft. and it was decided to design and construct a tower 1 ft. in diameter with a packed height of 15 ft. Coke was chosen as the packing (6) because it is cheap, inert to alkaline solution, available locally, fairly light in weight, and has a relatively large surface per unit volume. The gas to be used was to be either a mixture of air and carbon dioxide, or the flue gas from the combustion of natural gas, and in either case would contain from 10% to 12% carbon dioxide.

It was desired to absorb about 75% of the carbon dioxide. The method of Sherwood (7) was used to determine the operating characteristics of the above tower, using the data available in the literature.

First it was necessary to obtain the equilibrium curves for the system CO_2 - $NaHCO_3$ - Na_2CO_3 , and this was done by using the equation of Harte, Baker and Purcell (8):

(6) Badger & McCabe, "Elements of Chem. Eng.", p. 378.
(7) Sherwood, T.K., Absorption and Extraction.
(8) Harte, C.R., Baker, E.M., and Purcell, H.H., Ind. Eng. Chem., 25 , 528 (1933).

$$p_{CO_2} = \frac{137\, f^2 N^{1.29}}{S(1 - f)\,(365 - t)} \qquad \text{(VIII)}$$

Where p = the partial pressure of CO_2 in mm. Hg.

f = the fraction of total base present as bicarbonate

N = the sodium normality

S = solubility of CO_2 in water under a pressure of 1 atmos. of CO_2, gm. mols./l.

t = the temperature in F^o.

This equation is known to hold over the range from 65 to 150 F^o and for sodium normalities from 0.5 to 2.0.

Defining Y as mols. CO_2 per mol. of inert gas, then

$$p_{CO_2} = \frac{Y}{Y + 1} \qquad \text{(IX)}$$

$$Y = \frac{137\, f^2 N^{1.29}}{S\,(1 - f)\,(365 - t) - 137\, f^2 N^{1.29}} \qquad \text{(X)}$$

The values of Y (Table I) are calculated for various values of f at various temperatures and the data so obtained plotted as in Fig. II.

The tower was designed on the assumption that the gas used contained 11% CO_2 and that 75% of it was to be recovered. It was also decided that 2 N solution of sodium carbonate should be used. Some data on the decomposition of $NaHCO_3$ were obtained from the Liquid Carbonic Co. of Atlanta, Ga., and from these data it was logically concluded that the feed liquid would contain enough CO_2 to convert about 0.3 of the sodium to $NaHCO_3$ and that about 0.25 of sodium could be converted to $NaHCO_3$ in the tower so that the liquid leaving the

tower would have about 0.55 of the sodium converted to $NaHCO_3$.

TABLE I - EQUILIBRIUM DATA

t 70°F		t 80°F		t 90°F	
f	Y	f	Y	f	Y
0.00	0.0000	0.00	0.0000	0.00	0.0000
.10	.0004	.10	.0005	.10	.0006
.20	.0020	.20	.0024	.20	.0029
.30	.0054	.30	.0063	.30	.0075
.40	.0107	.40	.0130	.40	.0156
.50	.0203	.50	.0247	.50	.0296
.60	.0372	.60	.0453	.60	.0546
.70	.0695	.70	.0854	.65	.0745
.80	.4760	.75	.1218	.70	.1037
		.80	.1821	.75	.1485
t 100°F		t 110°F		t 120°F	
f	Y	f	Y	f	Y
0.00	0.0000	0.00	0.0000	0.00	0.0000
.10	.0007	.10	.0009	.10	.0010
.20	.0034	.20	.0039	.20	.0046
.30	.0087	.30	.0101	.30	.0120
.40	.0182	.40	.0213	.40	.0249
.50	.0347	.50	.0406	.50	.0477
.60	.0643	.60	.0755	.60	.0892
.65	.0882	.65	.1039	.65	.1233
.70	.1231	.70	.1459	.70	.1743
.75	.1780	.73	.1818		

TABLE I (cont'd.)

t 130°F		t 140°F		t 150°F	
f	Y	f	Y	f	Y
0.00	0.0000	0.00	0.0000	0.00	0.0000
.10	.0011	.10	.0014	.10	.0016
.20	.0053	.20	.0062	.20	.0072
.30	.0138	.30	.0160	.30	.0187
.40	.0287	.40	.0338	.40	.0395
.50	.0557	.50	.0653	.50	.0769
.60	.1049	.55	.0896	.55	.1060
.65	.1459	.60	.1240	.60	.1472
.70	.2081	.65	.1735	.63	.1805

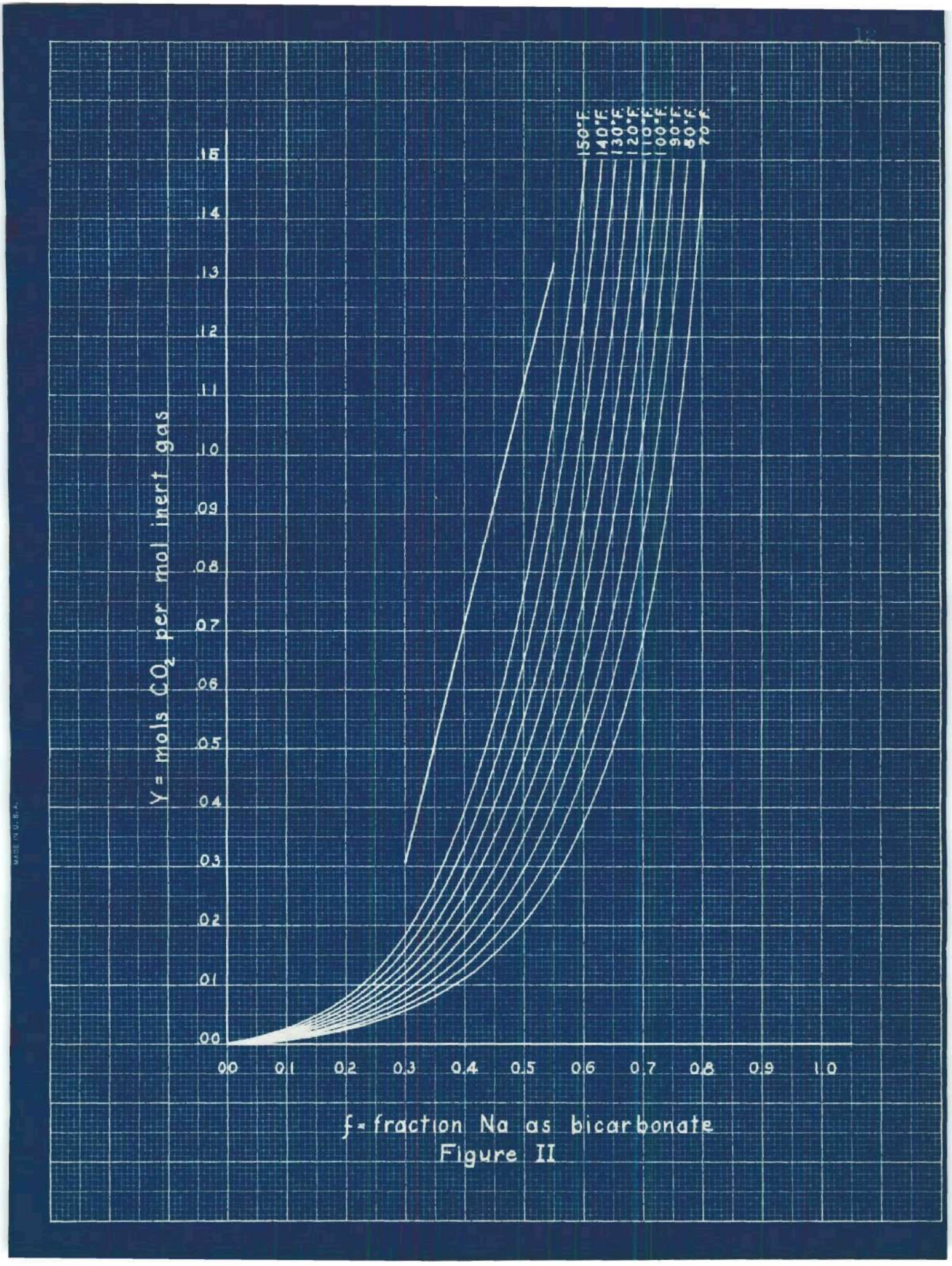

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
70°F.
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
f = fraction Na as bicarbonate

Figure II

The conditions of the operation may be tabulated as follows:

$f_1 = 0.55$ $\quad Y_o = 0.0309$ corresponding to 3% CO_2

$f_o = 0.30$ $\quad Y_1 = 0.1236$ corresponding to 11% CO_2

and from these conditions the operating line is drawn, Fig. II. The CO_2 absorbed is

$$\frac{F}{359} \times \frac{492}{460} \times 0.11 \times 0.75 = \frac{0.1131\ F}{460 + t} \text{ lb. mols/hr./sq.ft.}$$

Where F = the gas flow in cu. ft./hr./sq.ft. tower at a pressure of 1 atm.

The CO_2 equivalent of the sodium in the feed liquid is

$$L \times \frac{28.315}{68167} \times \frac{N}{2} \times \frac{1}{453.6} = 0.00045452\ LN \text{ lb. Mols./hr./sq.ft.} \qquad \text{(XI)}$$

where L = the liquid flow in lbs./hr./sq.ft. tower

and N = sodium normality of the solution

Inasmuch as it has been decided that the sodium conversion to $NaHCO_3$ in the tower is 0.55 - 0.30 = 0.25, the relation between L and F may be obtained by the equation

$$\frac{0.1131\ F}{460 + t} = 0.00045452\ LN \times 0.25$$

$$F = (0.94584 + 0.0020562\ t)\ L.$$

The absorption coefficient, according to the data of Byrne and Carlson (9), is expressed by the empirical equation

$$K_L' a = 0.000074\ t + 0.0000048\ L - 0.0055 \qquad \text{(XII)}$$

(9) Sherwood, T.K., "Absorption and Extraction", p.145, McGraw-Hill, 1937.

where $K_L'a$ is defined as $\frac{\text{lb. mols. } CO_2}{(\text{hr.})(\text{cu.ft.})(\text{unit driving force})}$

and the unit driving force is expressed as the difference in the expression $N (f_c - f)$. From the definition of $K_L'a$ and a material balance

$$0.00045452 \, LN \, df = (K_L' a) N (f_c - f) \, dh$$

and separating the variables

$$0.00045452 \, LN \, \frac{df}{f_c - f} \quad (K_L' a) N \, dh$$

$$K_L'a \; Nh = 0.00045452 \int_{.30}^{.55} \frac{df}{f_c - f}$$

Substituting

$$K_L'a = 0.000074 \, t + 0.0000048 \, L - 0.0055 \qquad \text{(XII)}$$

and solving for L

$$L = \frac{(0.74 \, t - 55) \, h}{4.5452 \int_{.30}^{.55} \frac{df}{f_c - f} - 0.048h}$$

Since $h = 15$ f t

$$L = \frac{11.1 \, t - 825}{4.5452 \int_{.30}^{.55} \frac{df}{f_c - f} - 0.72}$$

and from the above relation between L and F

$$F = \frac{780.32 - 8.80 \, t - 0.022823 \, t^2}{0.72 - 4.5452 \int_{.30}^{.55} \frac{df}{f_c - f}}$$

The integral $\int_{.30}^{.55} \frac{d}{f_c - f}$ was evaluated graphically by plotting $\frac{1}{f_c - f}$ against f for each temperature, Table II, and measuring the area under the curve between the limits $f = 0.55$ and $f = 0.30$ with a planimeter. (Figs. III, IV,

and V). The values obtained for $\int_{.30}^{.55} \frac{df}{f_c - f}$ are listed in Table III, and these values were then used to calculate L and G as in Table IV.

Naturally the optimum operating conditions are those under which the maximum amount of CO_2 is absorbed per unit time, and consequently the optimum temperature is slightly above 120° as shown in Figures VI and VII.

TABLE II - INTEGRATION DATA

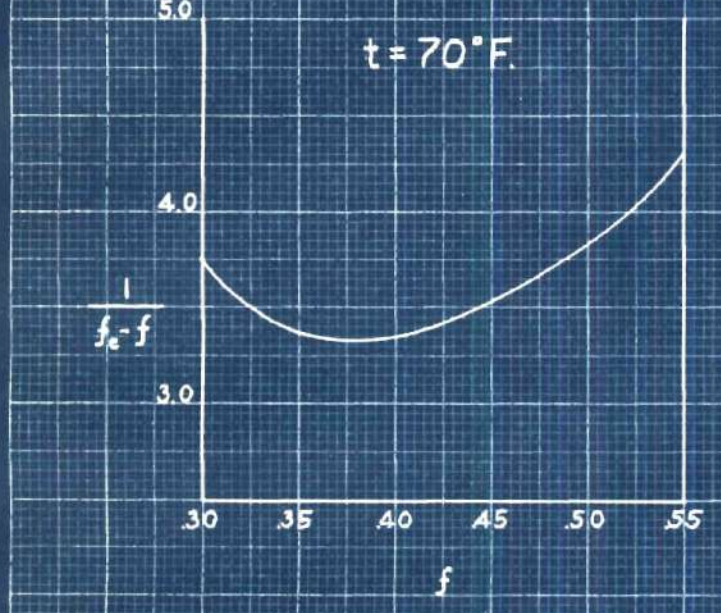
t 70°F			t 80°F		
f	$f_c - f$	$\frac{1}{f_c - f}$	f	$f_c - f$	$\frac{1}{f_c - f}$
0.30	0.268	3.73	0.30	0.235	4.25
.35	.297	3.37	.35	.262	3.82
.40	.298	3.35	.40	.260	3.74
.45	.283	3.53	.45	.252	3.97
.50	.260	3.84	.50	.230	4.35
.55	.232	4.31	.55	.202	4.95
t 90°F			t 100°F		
0.30	0.208	4.81	0.30	0.181	5.52
.35	.234	4.27	.35	.209	4.78
.40	.237	4.22	.40	.209	4.78
.45	.224	4.46	.45	.197	5.07
.50	.202	4.95	.50	.176	5.68
.55	.176	5.68	.55	.150	6.66

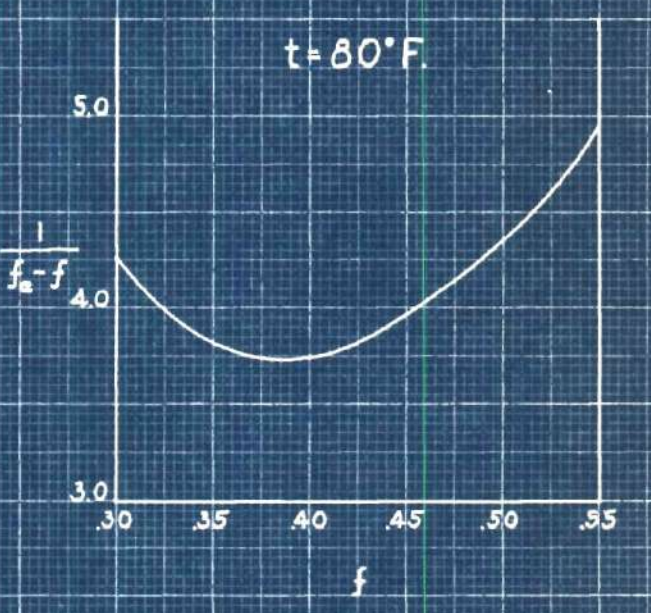
TABLE II (cont'd.)

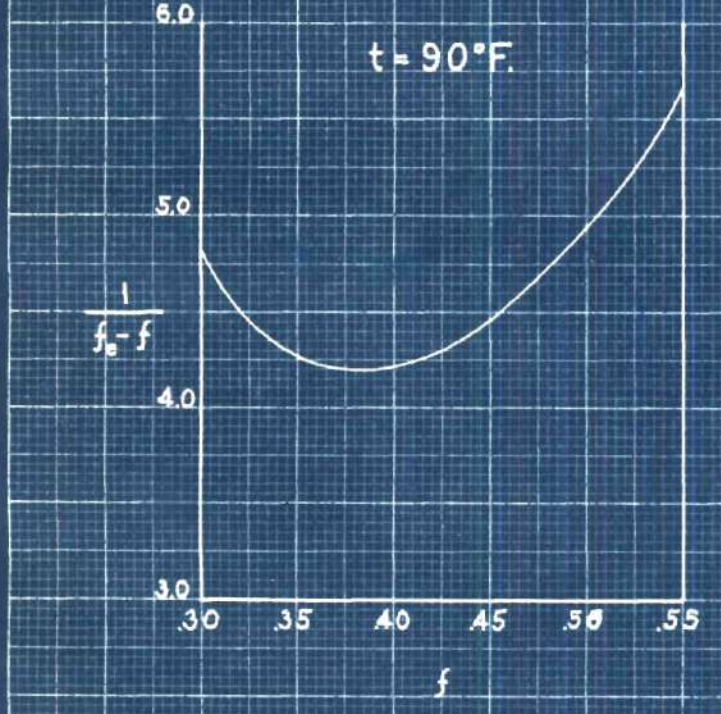
t 110°F			t 120°F		
f	f - f	$\frac{1}{f - f}$	f	f - f	$\frac{1}{f - f}$
0.30	0.156	6.41	0.30	0.132	7.57
.35	.182	5.50	.35	.156	6.41
.40	.183	5.46	.40	.158	6.33
.45	.172	5.81	.45	.147	6.80
.50	.151	6.62	.50	.125	8.00
.55	.127	7.87	.55	.101	9.90

t 130°F			t 140°F		
f	f - f	$\frac{1}{f - f}$	f	f - f	$\frac{1}{f - f}$
0.30	0.109	9.16	0.30	0.086	11.61
.35	.133	7.52	.35	.106	9.43
.40	.133	7.52	.40	.107	9.35
.45	.120	8.34	.45	.094	10.62
.50	.100	10.00	.50	.074	13.50
.55	.074	13.50	.55	.050	20.00

t 150°F		
f	f - f	$\frac{1}{f - f}$
0.30	0.062	16.12
.35	.084	11.90
.40	.084	11.90
.45	.070	14.29
.50	.049	20.20
.55	.023	43.50


t = 70°F.
5.0
4.0
3.0
$\frac{1}{f_e - f}$
.30 .35 .40 .45 .50 .55
f


t = 80°F.
5.0
4.0
3.0
$\frac{1}{f_e - f}$
.30 .35 .40 .45 .50 .55
f


t = 90°F.
6.0
5.0
4.0
3.0
$\frac{1}{f_e - f}$
.30 .35 .40 .45 .50 .55
f

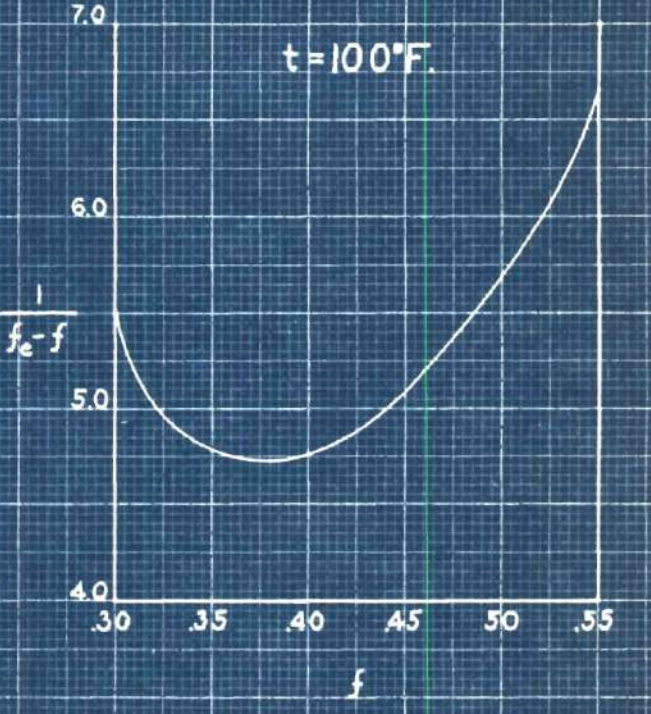

t = 100°F.
7.0
6.0
5.0
4.0
$\frac{1}{f_e - f}$
.30 .35 .40 .45 .50 .55
f

Figure III

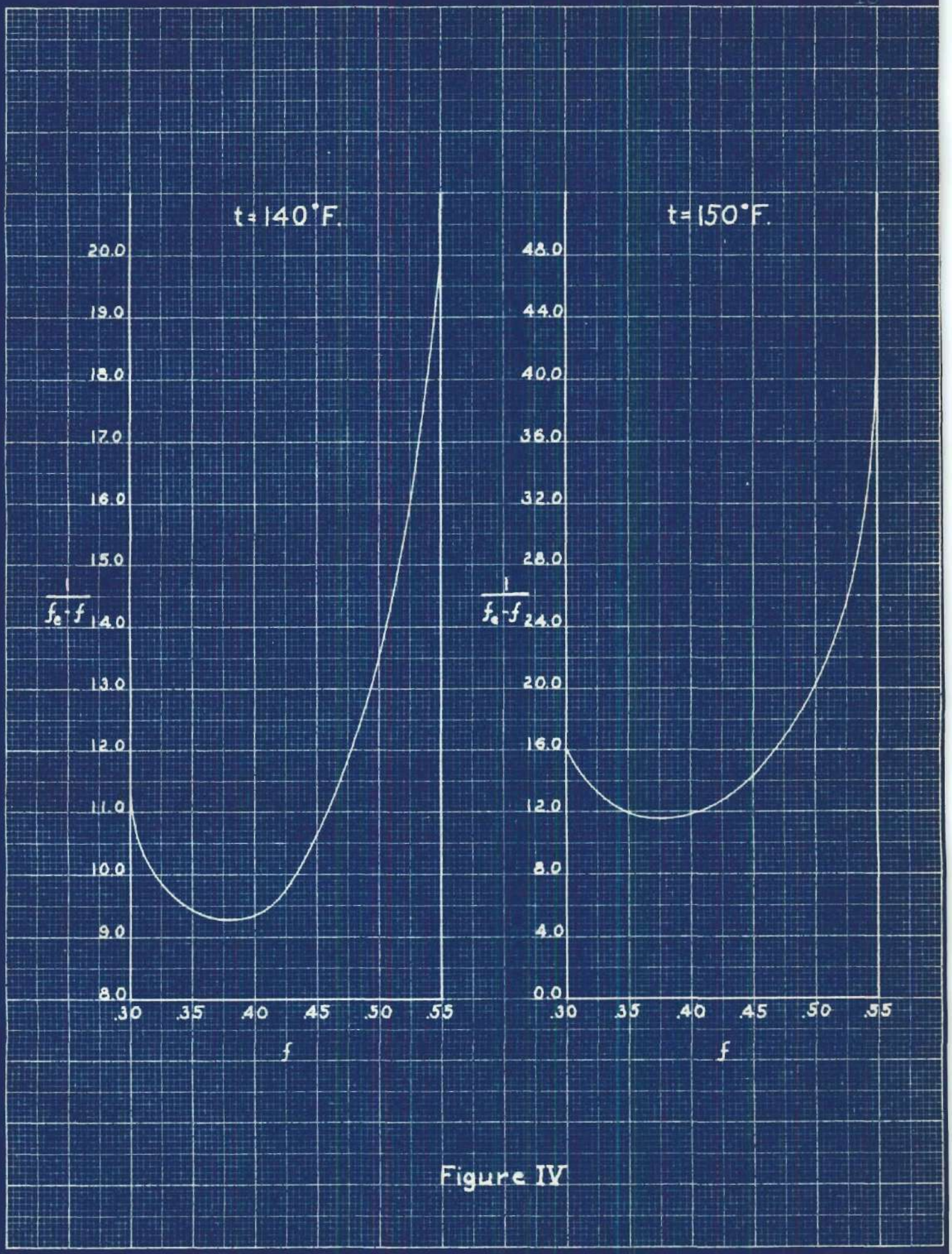

t = 140°F.
t = 150°F.
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
48.0
44.0
40.0
36.0
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0
$\frac{1}{f_e - f}$
.30
.35
.40
.45
.50
.55
f

Figure IV

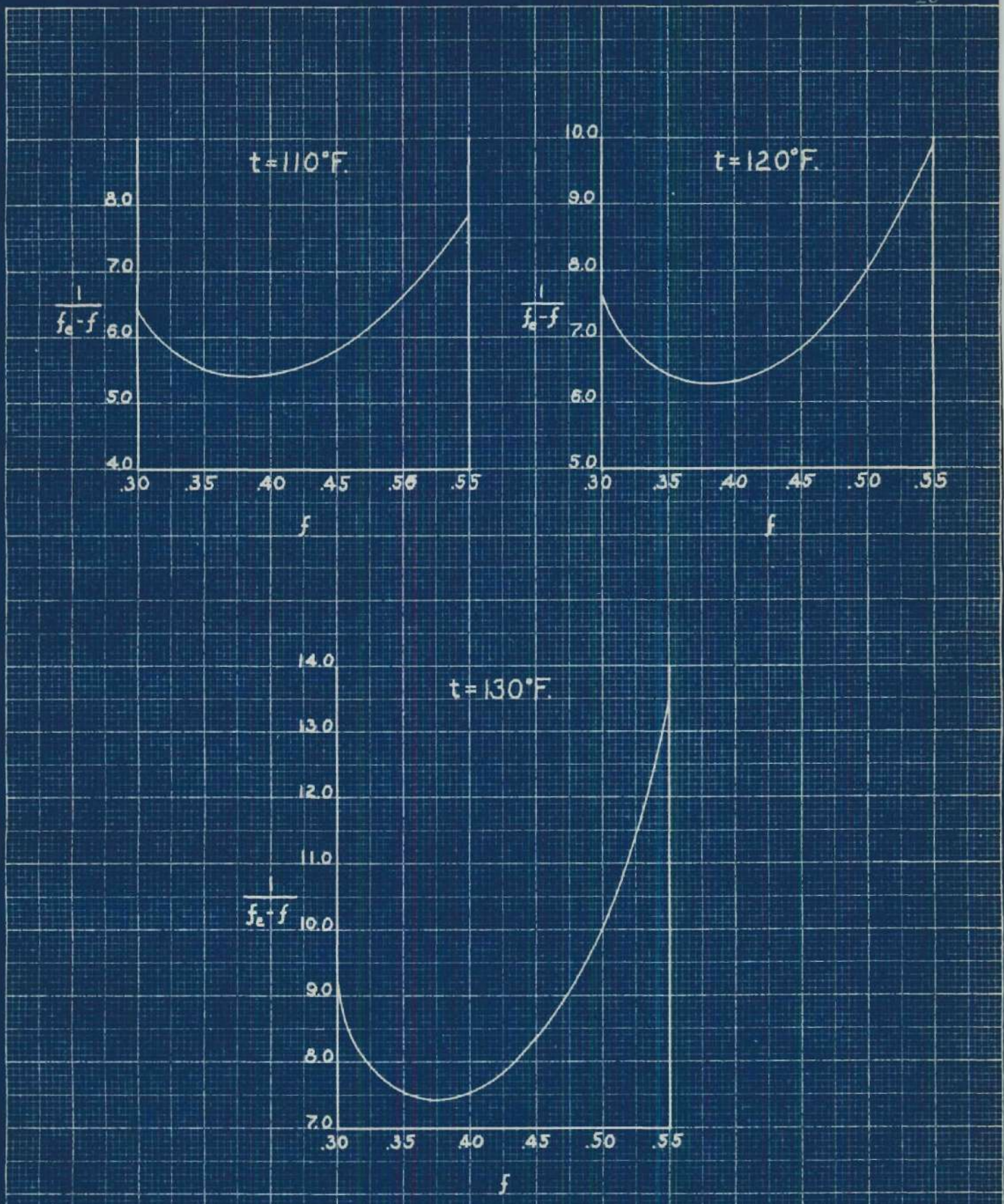

t=110°F.
8.0
7.0
6.0
5.0
4.0
1/(fc-f)
.30
.35
.40
.45
.50
.55
f
t=120°F.
10.0
9.0
8.0
7.0
6.0
5.0
1/(fc-f)
.30
.35
.40
.45
.50
.55
f
t=130°F.
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
1/(fc-f)
.30
.35
.40
.45
.50
.55
f

Figure V

TABLE III	
t °F	$\int_{.30}^{.55} \frac{df}{f_c - f}$
70	0.896
80	1.010
90	1.141
100	1.306
110	1.506
120	1.794
130	2.194
140	2.830
150	4.076

TABLE IV		
t °F	L	F
80	16.31	18.113
90	38.97	44.071
100	54.64	62.91
110	64.65	75.77
120	68.20	81.34
130	66.80	81.13
140	60.05	74.22
150	47.17	59.16

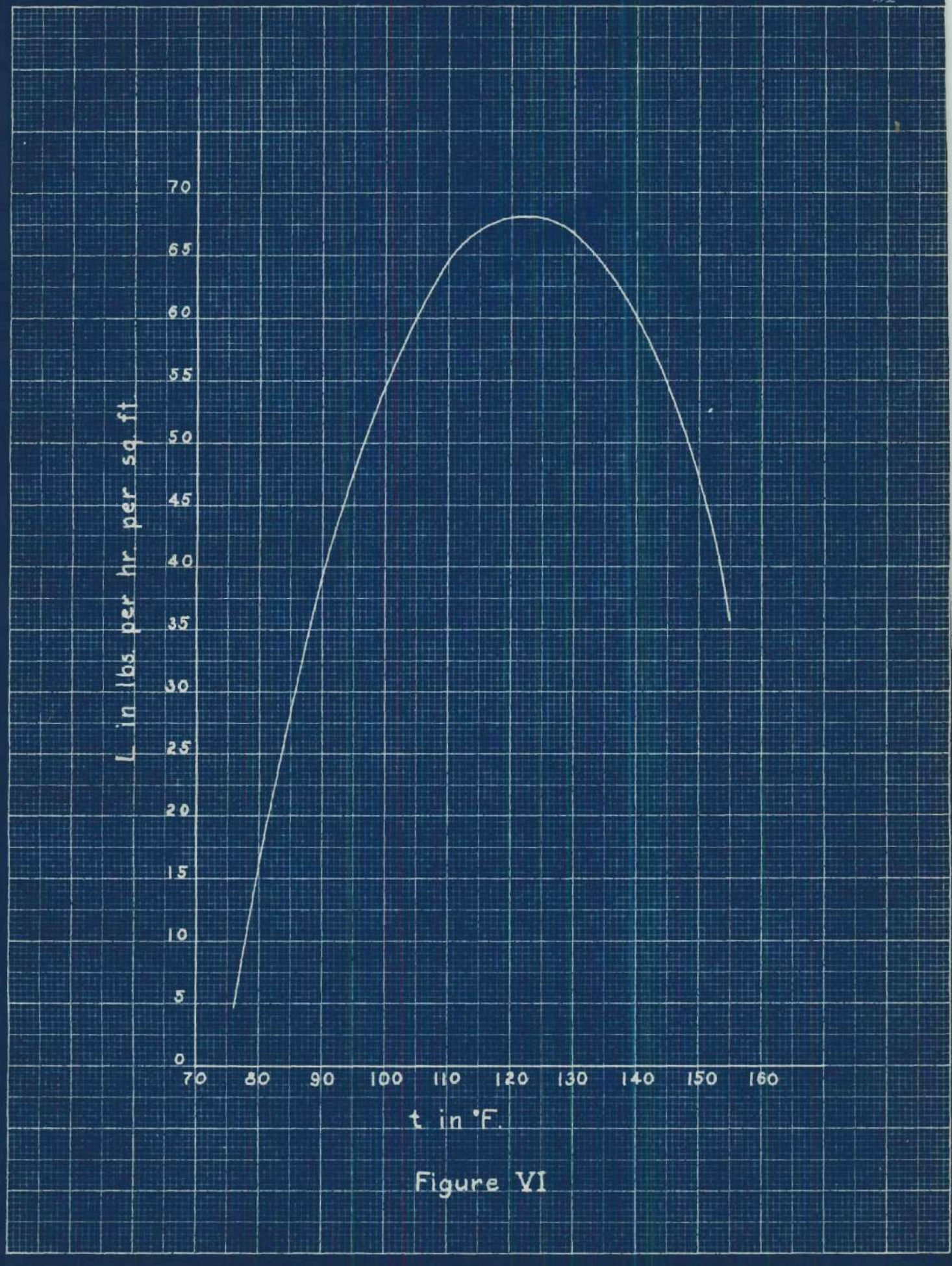

70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
L in lbs. per hr per sq. ft.
70
80
90
100
110
120
130
140
150
160
t in °F.

Figure VI

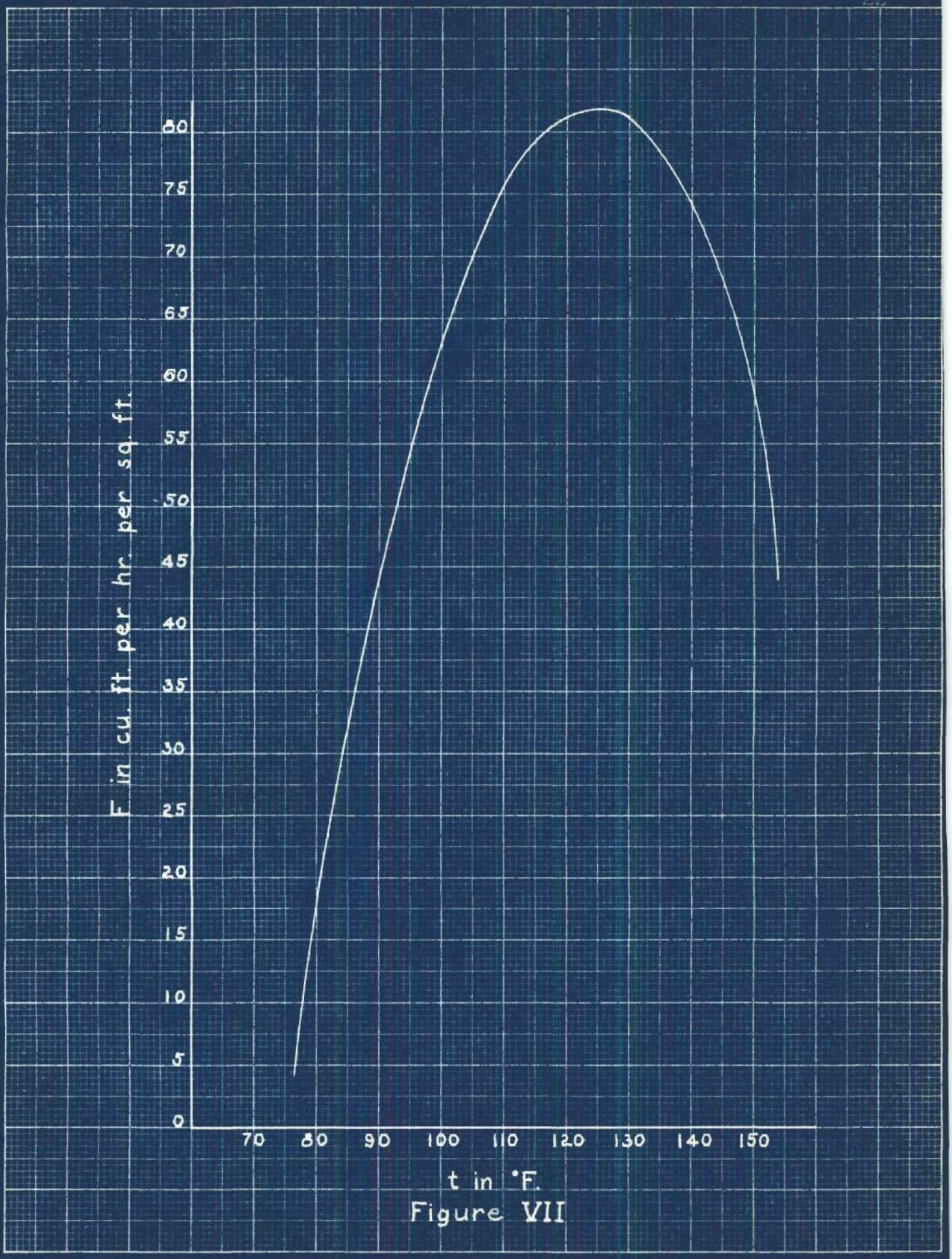

F in cu. ft. per hr. per sq. ft.
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
70
80
90
100
110
120
130
140
150
t in °F.

Figure VII

PART III - CONSTRUCTION

After a decision had been reached regarding the size of the tower, it was necessary to decide upon the material of which it was to be made, and the strength that would be required.

It was found from different sources (10) that ordinary mild steel would withstand the corrosive action of the Na_2CO_3 solution satisfactorily, so this material was used in the construction whenever possible. The materials of construction, means of support, and sizes are shown in Figures VIII and IX. In order to determine the necessary thickness of the tower walls, 35 lbs. per cu. ft. was used as the density of the 2" coke packing, and the pressure at the bottom of 15' of such packing was determined. It was assumed that the coke acted as a fluid (11), and the pressure therefore equals:

$$15 \times 35 = 525 \text{ lbs./sq.ft.}$$

Using 16000 lbs./sq. in. as the allowable stress in the low carbon steel (12) the necessary wall thickness of the tower is:

$$\frac{525 \times 1 \times 1}{2 \times 12 \times t} = 16000$$

$$t = \frac{525}{16000 \times 2 \times 12} = 0.001368 \text{ ins.}$$

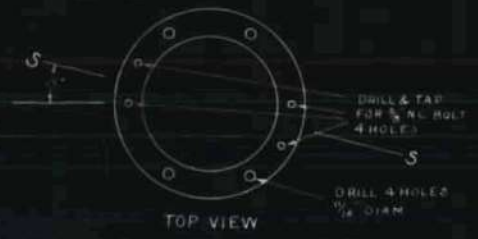
where t is the thickness in inches.

(10) Perry, J. H., Chemical Engineers Handbook, p. 1726, McGraw-Hill, '34. Process Industries Handbook of Corrosion Resistant Materials, p. 49, 130, 170, Chem. & Met. Eng., McGraw-Hill, 1931.

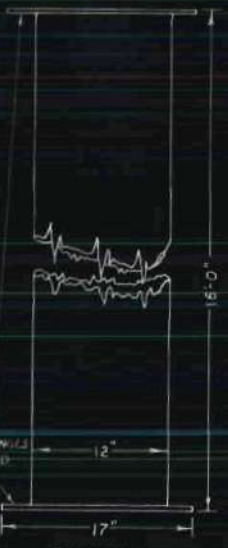
(11) Inasmuch as this in not true, the tendency of the packing to burst the tower will be less than that calculated.

(12) Suly, F.B., Resistance of Materials, p.428, John Wiley and Sons, 1935.

NOTE: In welding on Body Flanges, make sure that 4 top flange tapped holes are accurately over 4 bottom flange tapped holes, i.e. that line "S-S" is over "S'-S'"

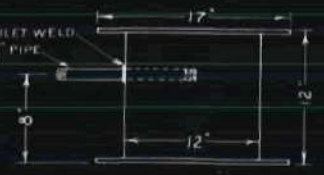


TOP VIEW



ELEVATION

TOP VIEW



ELEVATION

BOTTOM VIEW

TOWER BODY

OF 10 GA STEEL

BOTTOM VIEW

TOWER BOTTOM

TOP & BOTTOM FLANGES OF ⅜" PLATE, 17" D.

OF 10 GA. STEEL

TOP COVER LAYOUT

17" D ⅜" PLATE

LOWER PLATE FOR TOWER BOTTOM

SUPPORT PLATE

⅜" PLATE

Figure VIII

ABSORPTION TOWER

CHEM. ENGR. DEPT.

GEORGIA SCHOOL OF TECHNOLOGY

ATLANTA, GA

SCALE

0 1 2 FT.

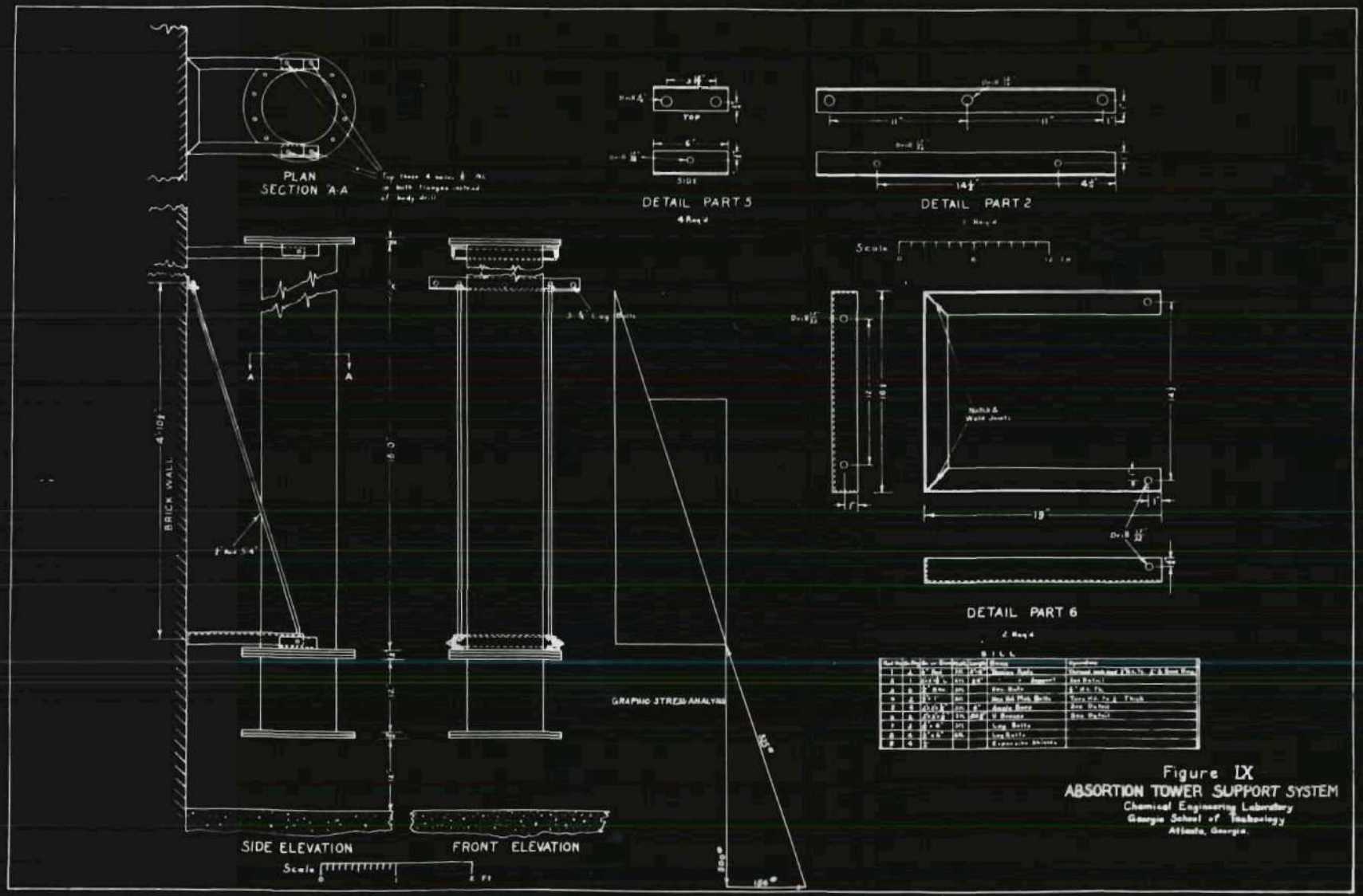


Figure IX
ABSORTION TOWER SUPPORT SYSTEM
Chemical Engineering Laboratory
Georgia School of Technology
Atlanta, Georgia.

If the tower were flooded, then the pressure would equal

$$62.4 \times 15 = 936 \text{ lbs./sq.ft.}$$

and

$$t = \frac{936}{16000 \times 2 \times 12}$$

$$= 0.00246 \text{ ins.}$$

In order to give the tower the required rigidity it was decided to construct it of 10 gauge steel, which has a thickness of 0.140 inches.

The volume of the steel in the tower is

$$17 \times \pi \times 1 \times \frac{.140}{12} = 0.623 \text{ cu. ft.}$$

for the sides of the tower,

$$4 \times \frac{3/8}{12} \times \pi \times \frac{(17 - 12)^2}{4 \times 12} = 0.017 \text{ cu. ft.}$$

$$3 \times \frac{3/8}{12} \times \pi \times \frac{(17/12)}{4} = 0.147 \text{ cu. ft.}$$

for the 3 plates.

The total volume = 0.623 + 0.017 + 0.147 = 0.787 cu. ft.

Using 489 lbs./cu. ft. as the density of steel, the weight of the tower is

$$0.787 \times 489 = 385 \text{ lbs., and}$$

the weight of the packing is

$$35 \times 15 \times \pi \times \frac{1^2}{4} = 413 \text{ lbs.}$$

The weight to be supported is

$$385 + 413 = 798 \text{ lbs.}$$

This is the dry weight and it was believed to be safe to assume that the total wet weight would be about 1000 lbs.

To support the tower as shown in Fig. IX, the rods would

each have to support a load of about 525 lbs. Again using 16000 lbs./sq. in. as the allowable stress, the rods would have to have the diameter shown in the following calculation::

$$\frac{525}{\frac{\pi \times D^2}{4}} = 16000$$

$$D^2 = \frac{525 \times 4}{16000\ \pi} = 0.0417$$

$$D = 0.204 \text{ ins.}$$

It was decided to use 1/2" rods of cold rolled steel. The bolts were sufficiently strong, inasmuch as 5/8" were used and there were two bolts carrying the same load as each rod. This type of support allows just the lower part of the tower to be removed, or the lower part and the packing may be removed simply by removing various bolts.

The actual task of fabricating the tower itself was given to the Southern Iron and Equipment Co. of Atlanta, Ga.

After the tower was located it was packed with two inch coke and then washed. It was necessary to construct and install the various accessories necessary for its operation. At first it was thought that compressed carbon dioxide would be satisfactory as a source of carbon dioxide, but after a trial it was found unsatisfactory, mainly due to the cost. As a result, a burner was installed in which natural gas was burned to form carbon dioxide and water:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

Theoretically, the resulting flue gas should contain 11.8% carbon dioxide on a moisture free basis, but actually it was found impossible to obtain more than about 11% carbon

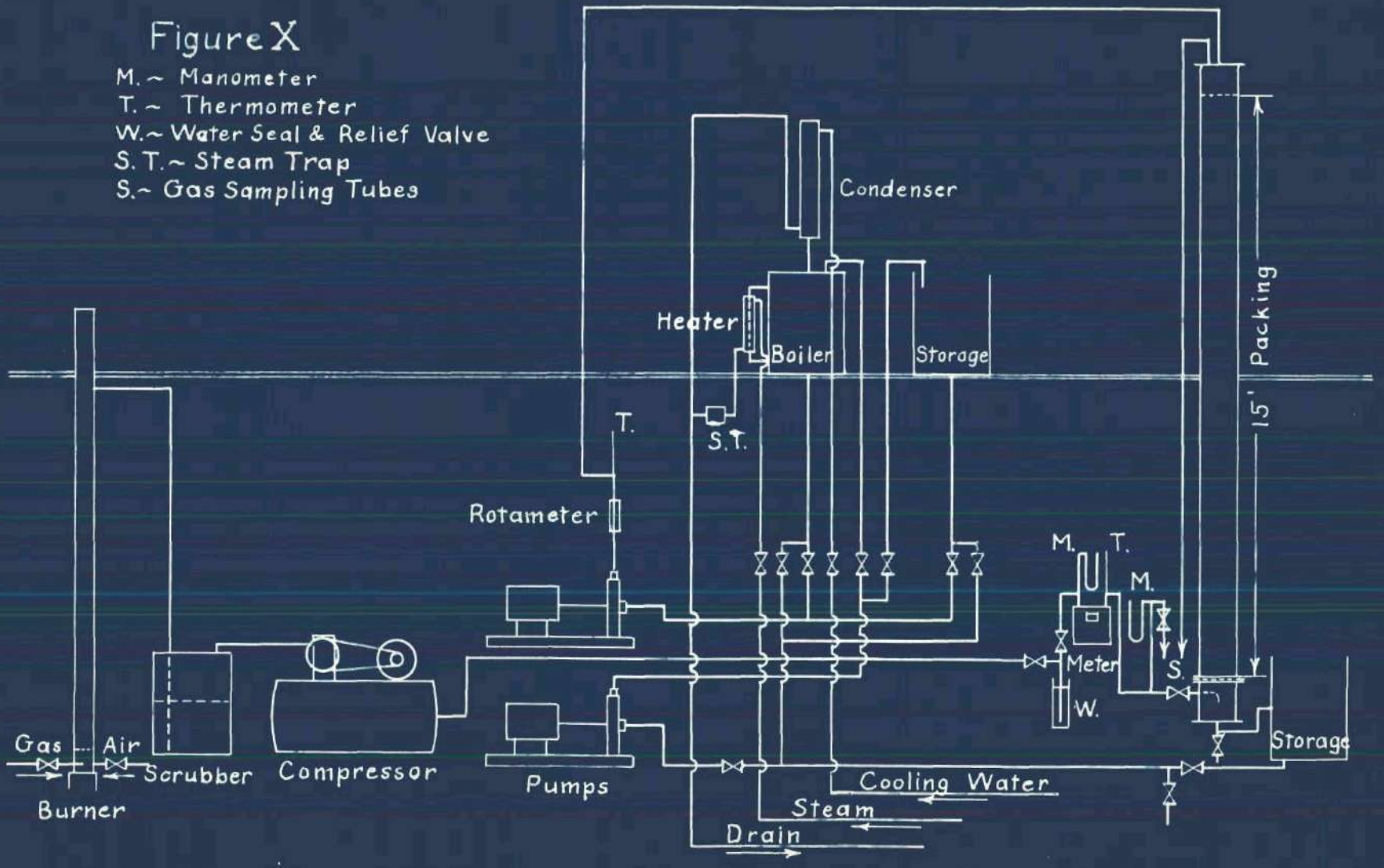
dioxide, and generally, slightly less than this was obtained.

A diagramatic sketch of the equipment is shown in Fig. X. The burner, Fig. XI, consists of a 5" iron pipe 12' long and fitted with a gas and an air supply and a grate. The gas and air were introduced on opposite sides of the burner, 3" from the bottom, and in such a manner that a whirling motion was produced, thus mixing the gases. A grate was located 9" from the bottom of the burner, and consisted merely of five parallel 3/16"x1" pieces of strap iron placed through slots cut into the sides of the burner. By carefully adjusting the amounts of gas and air introduced, a flue gas of the aforementioned analysis was obtained.

The gas was then cooled and scrubbed in a scrubber which consisted of a 50 gallon drum half filled with water and with the intake from the burner passing to the bottom of the drum. The gas was withdrawn from the top of the scrubber. This treatment saturates the gas with water vapor, as well as cooling it, and therefore the volume of the water vapor passing through the system is known. The gas was then taken from the scrubber and drawn into a compressor, where it was compressed just sufficiently to send it through the rest of the system. It passed through a gas meter, which was borrowed from the Atlanta Gas Co., and into the bottom of the tower. A relief valve, consisting of a pipe dipping into a jar of water, was provided on the inlet side of the meter because the maximum operating pressure of the meter was 2 lbs./sq.in. A water manometer was provided to measure the pressure of the gas before it entered the meter,

Figure X

M. ~ Manometer
T. ~ Thermometer
W. ~ Water Seal & Relief Valve
S. T. ~ Steam Trap
S. ~ Gas Sampling Tubes



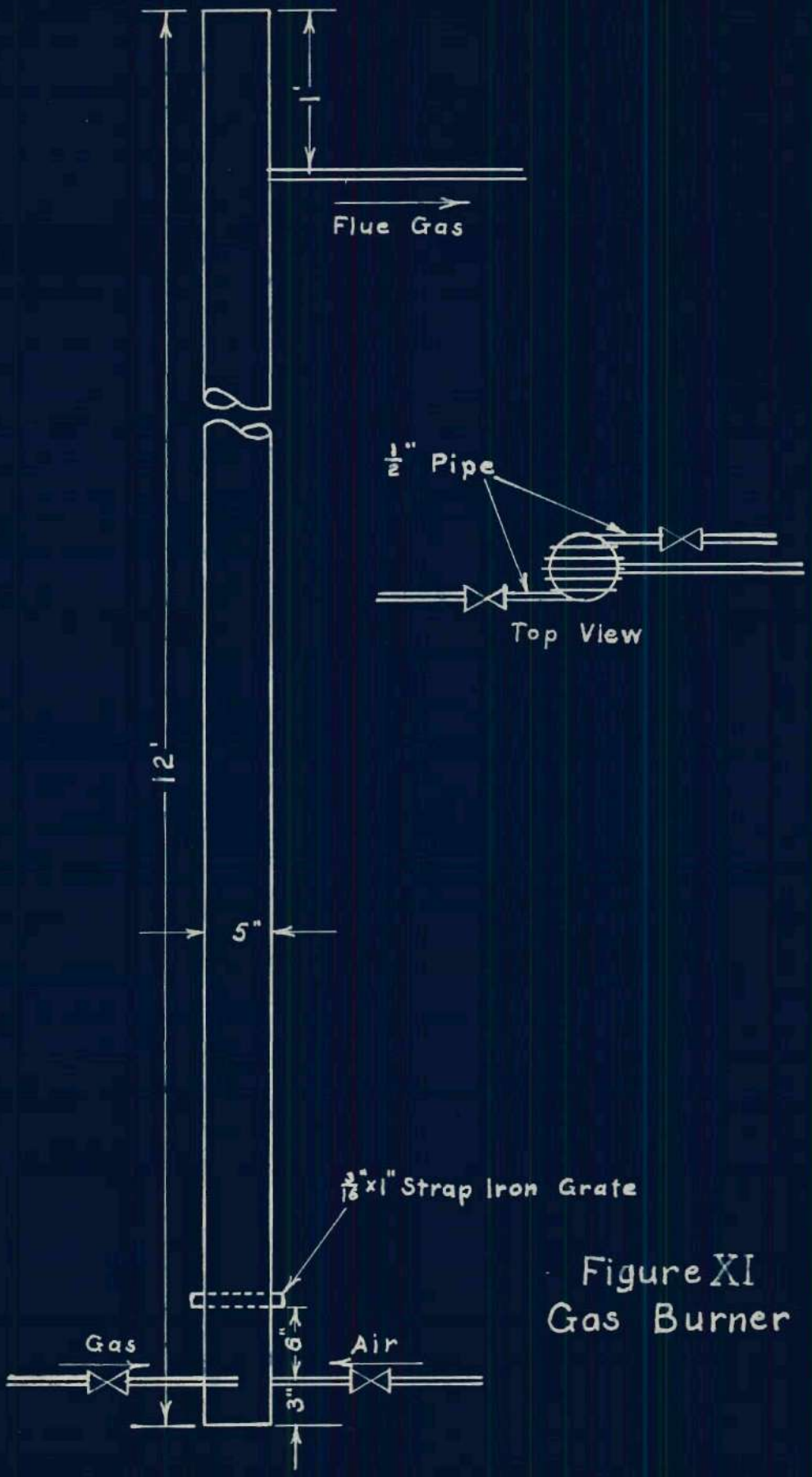


Figure XI
Gas Burner

and a thermometer and a water manometer were provided to measure the temperature and pressure of the gas before it entered the tower. The two manometers were necessary because there was a pressure drop through the meter. A sampling tube was also provided for in order to obtain a sample of the gas before it entered the tower. The gas then passed upward through the tower and a means was provided to obtain a sample of the exhaust gas.

Circulation of the liquid was provided for by purchasing two type 1-C Gardener-Denver centrifugal pumps equipped with three phase, 220 v., 1150 R. P. M., 1/4 H. P. motors. The liquid system consists of storage space, a lye boiler where the lye is regenerated, a measuring device, in this case a rotameter, and a temperature measuring device, a thermometer. The units of the system were connected in such a manner that the lye could be pumped from storage to the boiler or vice versa, and from either the storage or the boiler to the tower through the rotameter, Fig. X.

The lye boiler was constructed of a 50 gallon drum equipped with an external tubular steam heater, a condenser, a sight glass, and an inlet and outlet and mounted 10 ft. off the floor. The storage consisted of two 50 gallon drums with the heads removed, one at the base of the tower and the other mounted at the same level as the lye boiler. The raised storage was equipped with a sight glass. The lye was drawn either from the raised storage or the lye boiler through the pumps, then the rotameter, and sprayed into the tower through three 1/4"

brass spray nozzles located approximately 9" from the top of the packing (13). The temperature was measured at the rotameter by a thermometer.

(13) In some instances brass parts were used because steel parts were very difficult to obtain. While brass is not as corrosion resistant as steel, it can be used.

Part IV

Operation

To operate the tower it is only necessary to pump the absorbing liquid into the top of the tower and introduce the flue gas into the bottom of the tower. At regular intervals the necessary data and samples are taken. The data taken consisted of the pressure and temperature of the gas at the meter, the pressure of the gas at the tower inlet, the rate of flow of the gas, the rate of flow of the liquid, and the temperature of the liquid. Samples of the inlet and exhaust gas and the inlet and outlet liquid were taken. The gas samples were analyzed for carbon dioxide and the inlet and outlet liquid was analyzed for its carbonate and bicarbonate content and the specific gravity of the inlet liquid was determined.

The following methods and procedures were used in making the aforementioned analysis. The gas samples were analyzed in a portable Orsat gas analysis apparatus and only the carbon dioxide was determined, the remaining gases were assumed to be inert gases. To analyze the liquid, a 50 cc. portion of the sample was pipetted out and diluted to 250 cc. in a volumetric flask. In as much as the liquid was approximately 2 N, this procedure gives approximately .5 N aliquots. The first 22 analyses were made by taking 50 cc. aliquots of this solution, adding phenolphthalein and titrating to the end point with standard acid. Then methyl orange was added to the same aliquot and the titration continued to a second end point. The phenolphathalein indicated the sodium present as the carbonate and the methyl

orange indicated the total sodium.

Under these conditions the phenolphthalein end point was found to be very hard to detect so the above procedure was discarded and the following procedure adopted (14).

To determine the bicarbonate content, a 50 cc. aliquot, diluted as before, was taken and 25 cc. of standard base approximately .5 N was added. This converts all of the bicarbonate into the carbonate. Then 20 cc. of a 20% $BaCl_2 \cdot 2H_2O$ solution was added to remove the carbonate ion and the excess base was titrated with standard acid using phenolphthalein as the indicator. Previously a blank, consisting of 25 cc. of the standard base and 20 cc. of the barium chloride solution, had been titrated with the standard acid. The difference between the blank titration and the sample titration gives the bicarbonate content.

The standard acid was prepared by diluting concentrated hydrochloric acid to approximately .5 N and standardizing with accurately weighed samples of sodium carbonate which had been especially prepared and dried. About five gallons of acid was prepared and standardized and was .5135 N. Standard base was made up to exactly the same strength.

To begin operation of the tower the burner was lighted and the flue gas compressor started. Then gas samples were taken periodically and analyzed for their carbon dioxide and oxygen content and the burner was adjusted until the oxygen

(14) Kolthoff, I.M. and Sandell, E. B., Textbook of Quantitative Inorganic Analysis, page 527. The Macmillan Co., 1936,

content was as low as possible without the formation of carbon monoxide (15). Meanwhile the liquid was being heated to the operating temperature or slightly higher in the lye boiler. The liquid had previously been regenerated, which operation requires about ten hours of boiling. The liquid was pumped out and back into the top of the lye boiler to insure mixing during the regenerating and heating processes.

When the liquid was heated to the desired temperature both the liquid and gas were circulated thru the tower at the desired rate. Data were not taken for an hour or more after commencing the flow of liquid and gas thru the tower so that equilibrium could be reached. After this preliminary period data were taken every fifteen to thirty minutes.

Tables V and VI list the experimental data as they were taken. The figures given in the column headed gas rate are the time, in seconds, required for the flow of two cubic feet of the gas thru the meter. The pressure at the meter and the tower is given in inches of water. The figures given in the column headed liquid rate are the rotameter readings and the calibration curve for this instrument is shown in Fig. XII. The figures in the columns headed HPh and M O are the phenolphthalein and the methyl orange titrations respectively. The character, f , represents the fraction of the sodium present as the bicarbonate and is calculated in the following manner:

(15) The gas used during the first 16 sets of data was a mixture of air and carbon dioxide, obtained from a cylinder. this proved unsatisfactory as was previously stated.

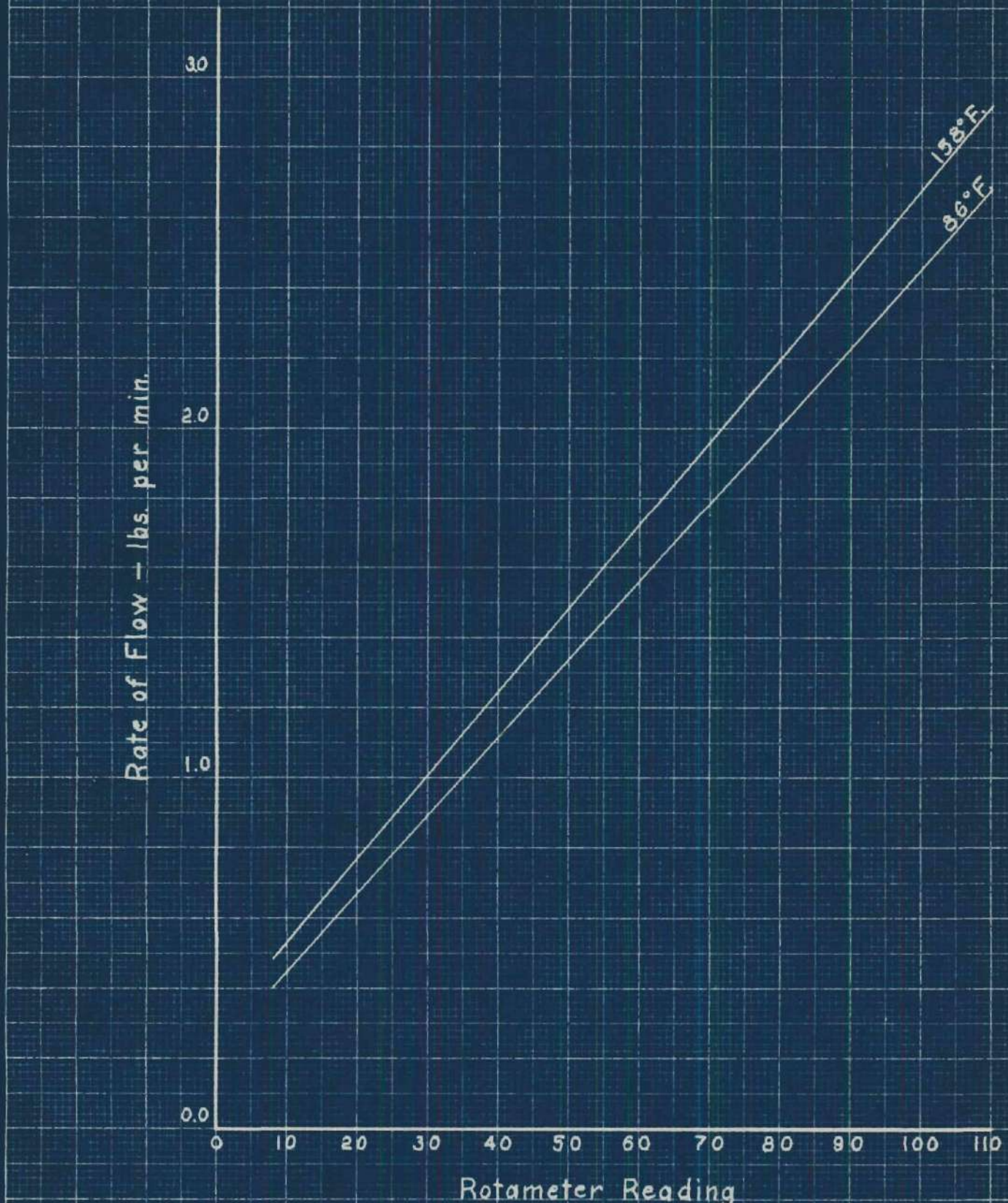

Rate of Flow - lbs. per min.
3.0
2.0
1.0
0.0
0
10
20
30
40
50
60
70
80
90
100
110
Rotameter Reading
138°F.
86°F.

Figure XII

For the first 22 sets of data

$$f = \frac{MO - 2H\ Ph}{MO}$$

For the rest of the data

$$f = \frac{blank - H\ Ph}{MO}$$

and the blank titration = 24.7 cc.

In order to determine the absorption coefficient $K_L'a$ the following calculations were necessary.

The CO_2 absorbed is $0.00045452LN(f_1 - f_2)$ lb.mols./hr. per sq.ft., Equation No. XI ,.By definition, $K_L'a$ is the lb. mols. CO_2 absorbed per hour per cu. ft. of tower per unit driving force, and the unit driving force is expressed as the product of $N(f_c - f)$. The unit driving force was determined for each set of data by plotting the operating line from the terminal conditions and determining the area between it and the equilibrium curve. If this area is divided by the ordinate which is $Y_1 - Y_2$ then the true average driving force, $(f_c - f)$, is obtained. The equilibrium curves with areas measured indicated on them are shown in Figures XIII - XIX.

Sample calculations for datum No. 23 are shown below.

$$N = \frac{MO \times 5 \times 0.5135}{50} \quad \text{where } 0.5135 = N \text{ acid}$$

$$= \frac{39.75 \times 5 \times 0.5135}{50} = 2.041\ N$$

$$CO_2 \text{ absorbed} = 0.00045452 \times 166 \times 2.041(0.391 - 0.264)$$

$$= 0.00045452 \times 166 \times 2.041 \times 0.127$$

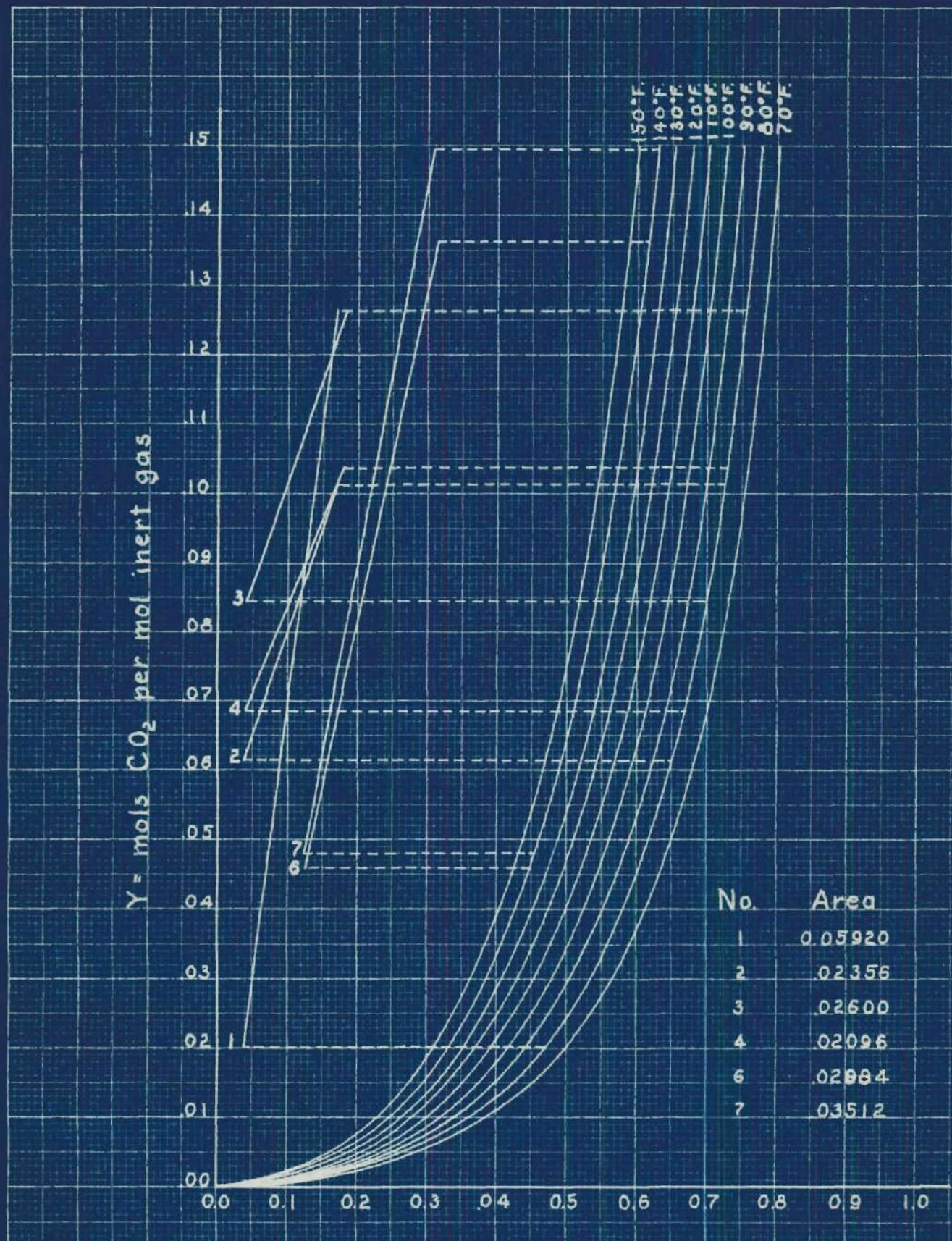

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
70°F.
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
0.0
0.1
0.2
0.3
.04
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4
6
7
No. Area
1 0.05920
2 .02356
3 .02600
4 .02096
6 .02884
7 .03512
f = fraction Na as bicarbonate

Figure XIII

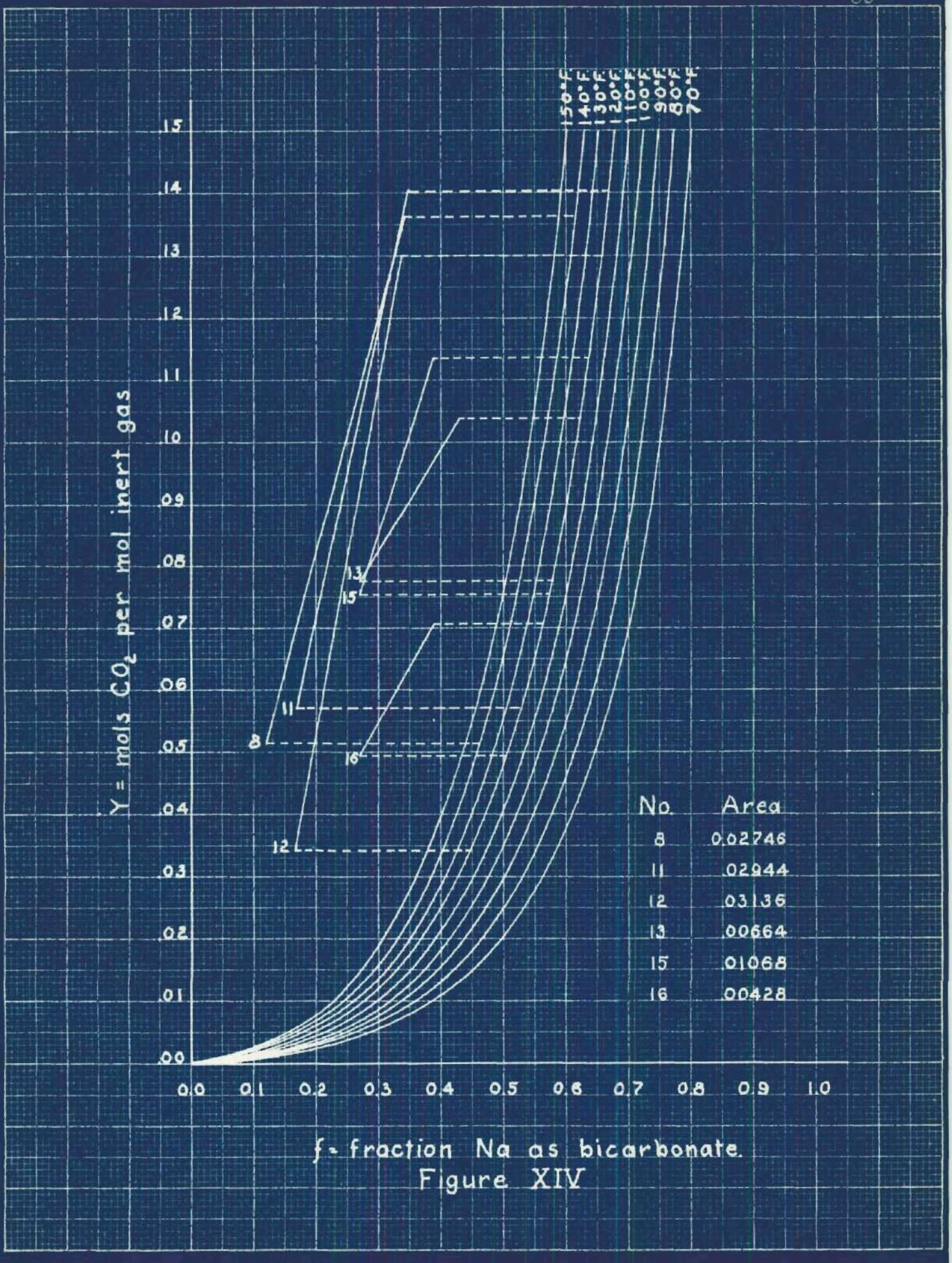

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
70°F.
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
8
11
12
13
15
16
No. Area
8 0.02746
11 .02944
12 .03136
13 .00664
15 .01068
16 .00428
f = fraction Na as bicarbonate.

Figure XIV

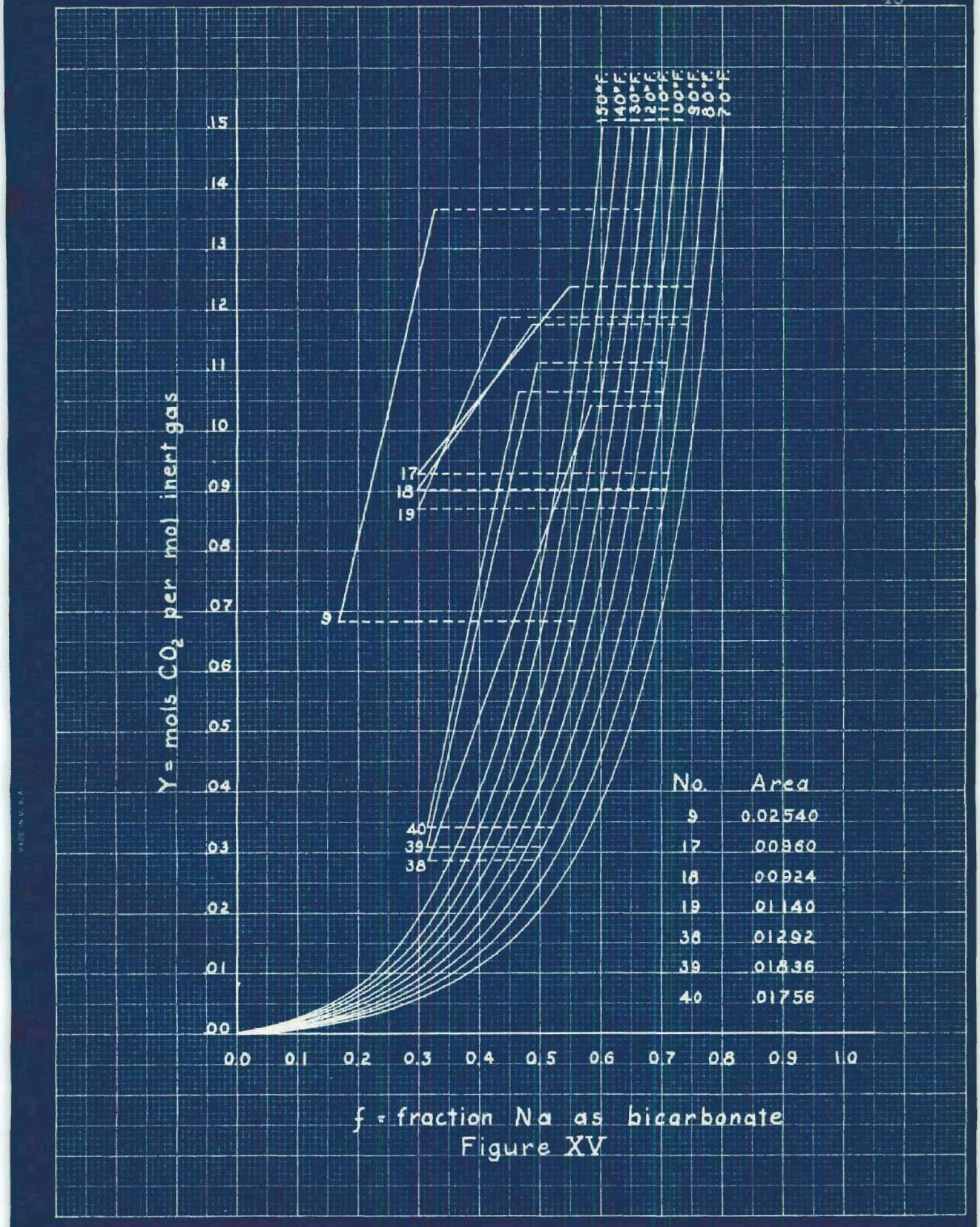

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
f = fraction Na as bicarbonate
9
17
18
19
38
39
40
No. Area
9 0.02540
17 .00960
18 .00924
19 .01140
38 .01292
39 .01836
40 .01756

Figure XV

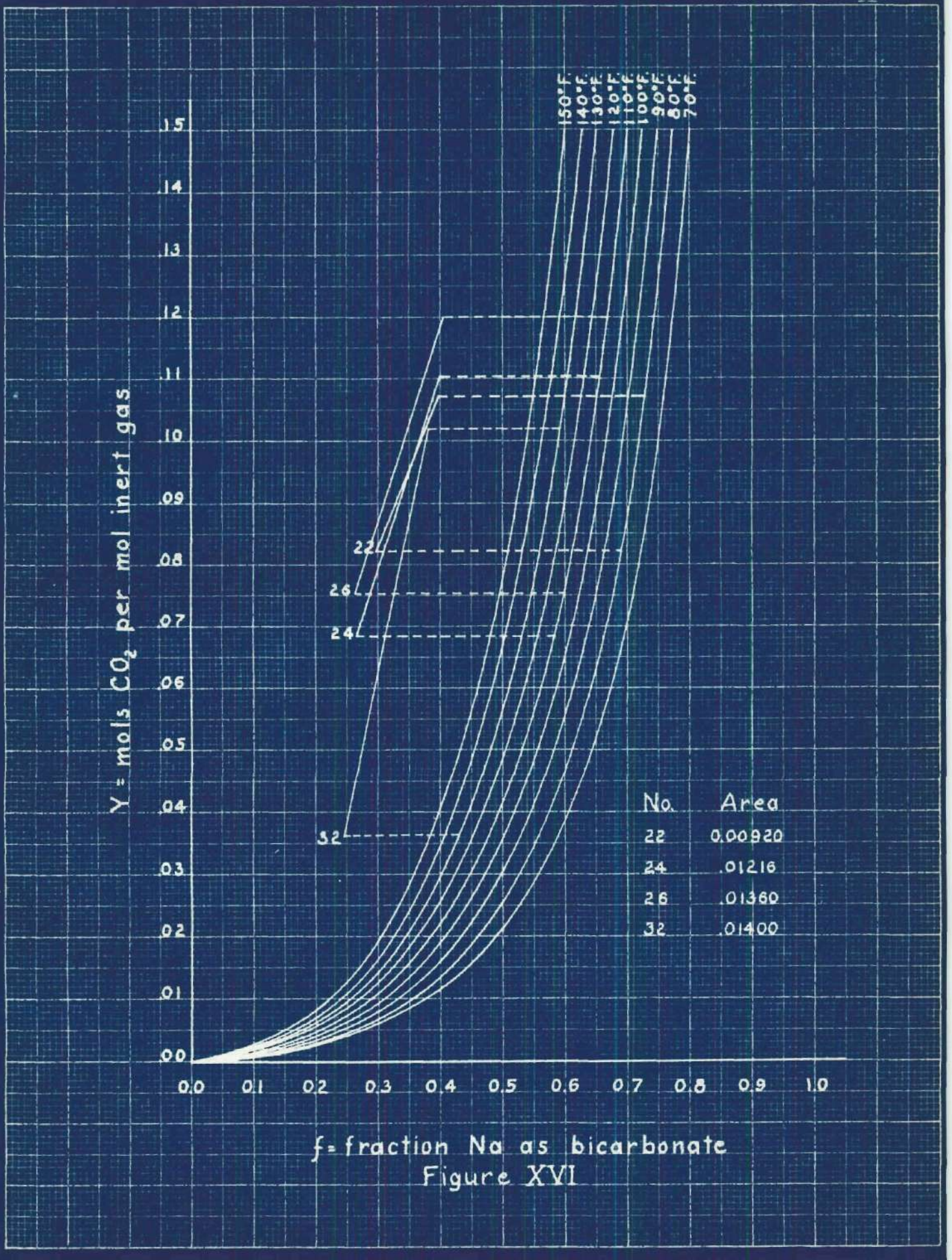

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
70°F.
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
Y = mols CO_2 per mol inert gas
22
26
24
32
No. Area
22 0.00920
24 .01216
26 .01360
32 .01400
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
f = fraction Na as bicarbonate

Figure XVI

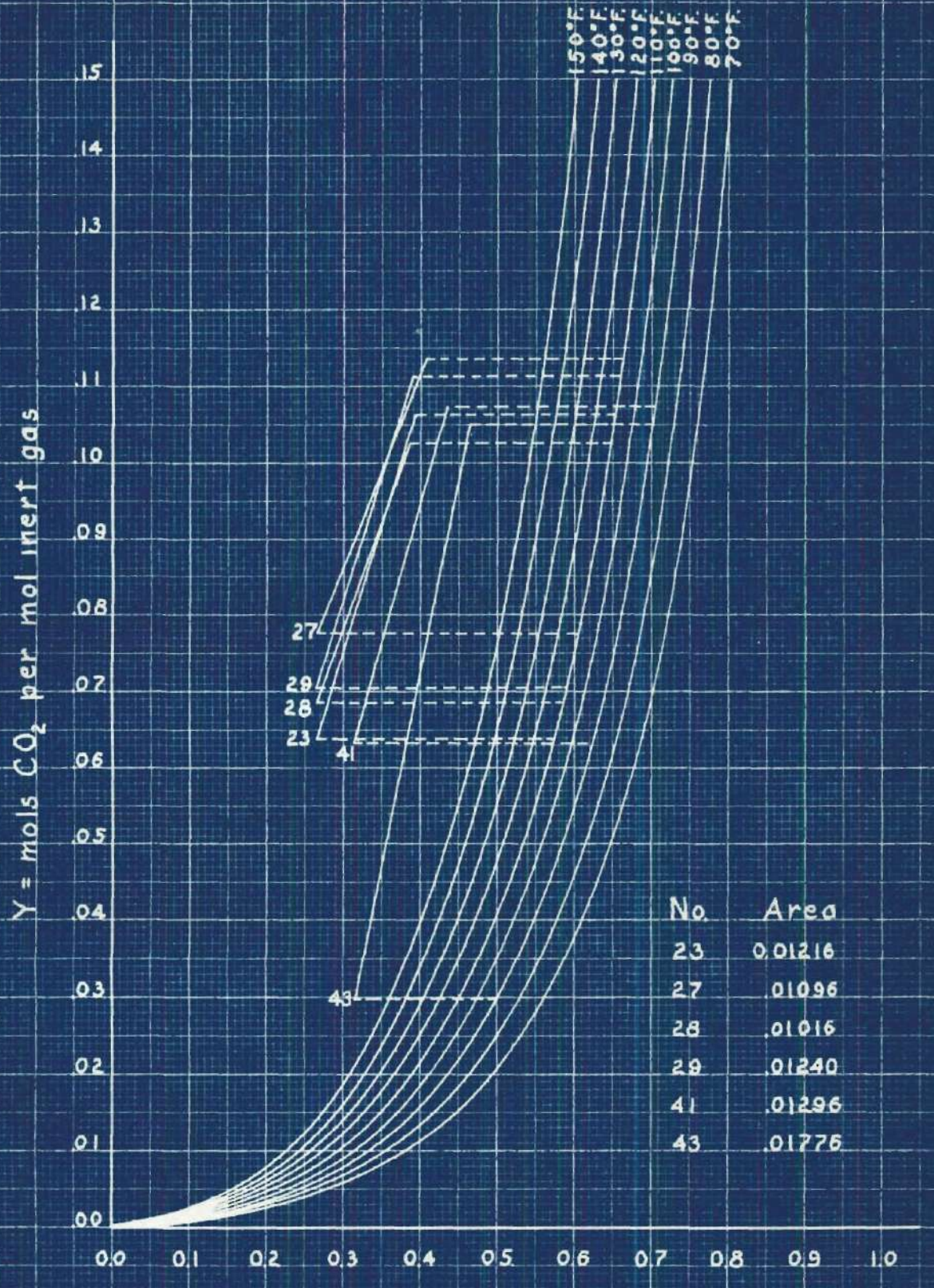

150°F.
140°F.
130°F.
120°F.
110°F.
90°F.
80°F.
70°F.
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
27
29
28
23
41
43
No. Area
23 0.01216
27 .01096
28 .01016
29 .01240
41 .01296
43 .01776
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
f = fraction Na as bicarbonate

Figure XVII

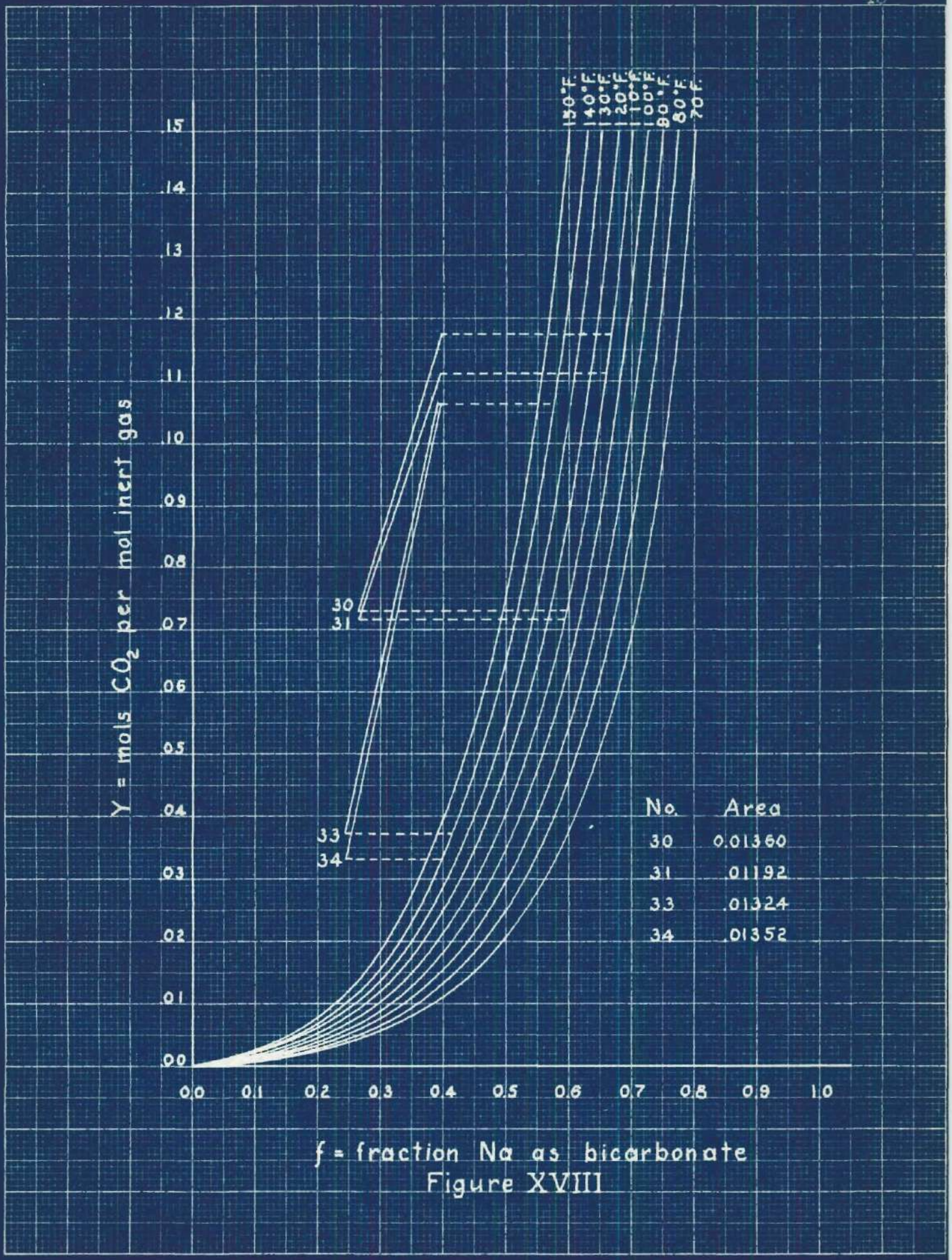


Figure XVIII

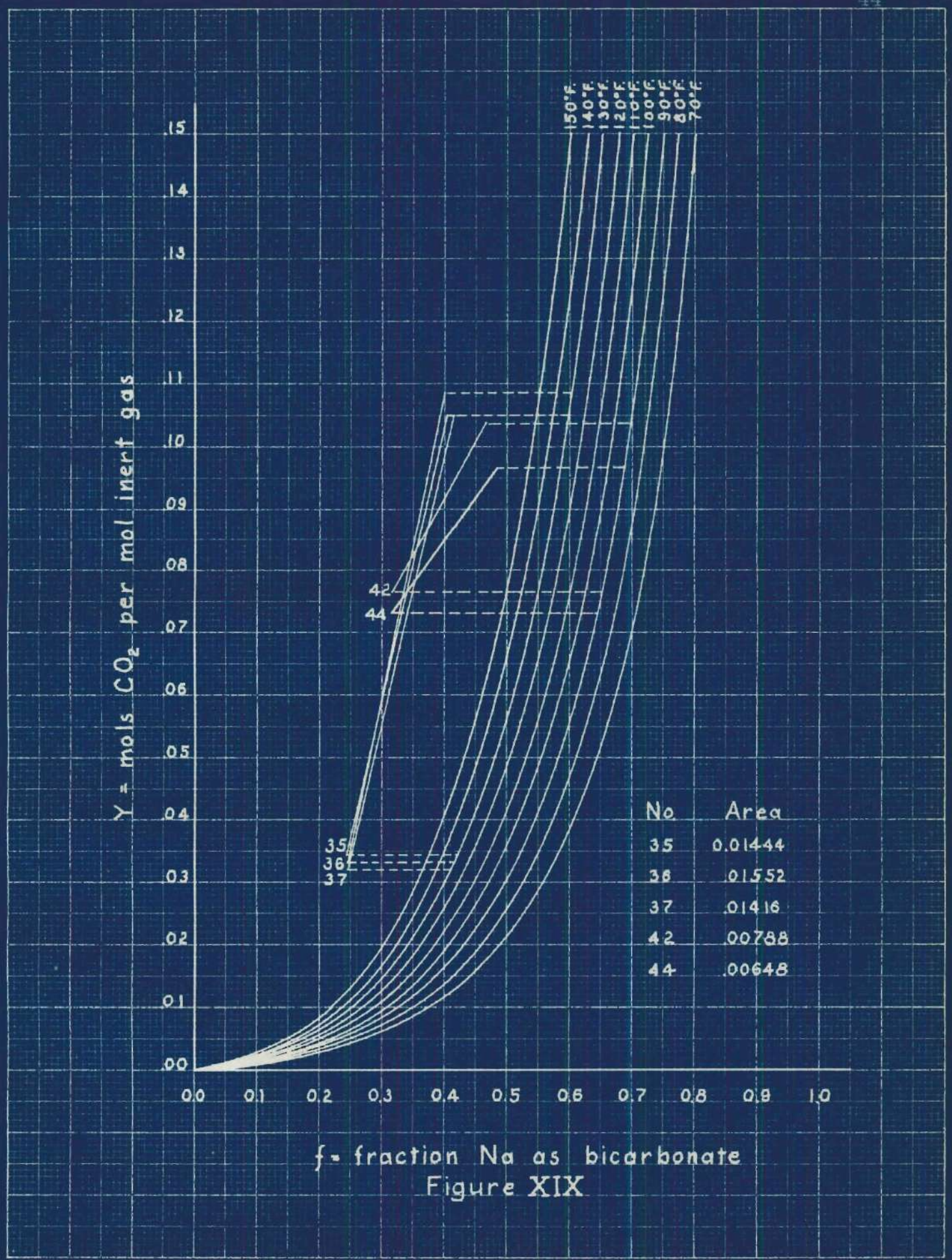

150°F.
140°F.
130°F.
120°F.
110°F.
100°F.
90°F.
80°F.
70°F.
42
44
35
36
37
Y = mols CO_2 per mol inert gas
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
f = fraction Na as bicarbonate
No Area
35 0.01444
36 .01552
37 .01416
42 .00788
44 .00648

Figure XIX

TABLE V - EXPERIMENTAL DATA

GAS

No.	Rate	Temp.	Pressure			Analysis	
			Baro.	Meter	Tower	Inlet	Outlet
		°F	mm. Hg.	in. H_2O	in. H_2O	$\%CO_2$	$\%CO_2$
1	36.0	74	735	4.6	0.8	11.4	2.0
2	36.0	75	735	5.0	1.1	9.2	5.8
3	32.7	74	735	7.7	1.6	11.4	7.8
4	32.7	72	735	7.7	1.8	9.4	6.4
5	36.0	79	738	3.0	0.8	13.0	---
6	36.0	79	738	3.5	0.8	12.0	4.4
7	36.0	81	738	3.5	0.9	13.0	4.6
8	36.0	81	738	3.5	0.9	12.0	4.9
9	47.0	79	742	3.0	0.5	12.0	6.4
10	47.8	79	742	3.0	0.6	11.2	5.2
11	48.1	81	742	3.2	0.5	12.3	5.4
12	48.3	81	742	2.6	0.6	11.5	3.3
13	31.8	73	740	6.3	1.7	9.4	7.2
14	32.2	71	740	6.3	1.7	7.8	5.3
15	31.8	69	740	6.3	1.8	10.2	7.0
16	32.0	69	740	6.3	1.9	6.6	4.7
17	31.6	82	735	5.9	1.0	11.0	8.5
18	31.9	83	735	6.1	1.3	10.5	8.2
19	32.9	82	735	6.2	1.3	10.6	8.0
20	32.6	82	735	6.2	1.3	9.6	7.6
21	31.8	81	735	6.1	1.3	10.2	7.8
22	31.7	82	735	6.0	1.4	9.7	7.6

TABLE V (cont'd)

GAS

No.	Rate	Temp.	Pressure			Analysis	
			Baro.	Meter	Tower	Inlet	Outlet
		°F	mm. Hg.	in. H_2O	in. H_2O	$\%CO_2$	$\%CO_2$
23	45.5	80	736	2.4	1.5	9.6	6.0
24	44.6	79	736	2.2	1.6	10.0	6.4
25	45.0	79	736	2.3	1.6	10.8	6.8
26	44.7	79	736	2.3	1.6	10.7	7.0
27	44.7	79	736	2.3	1.7	10.2	7.2
28	45.2	79	736	2.3	1.7	9.3	6.4
29	44.0	78	736	2.3	1.7	10.0	6.6
30	44.7	78	736	2.3	1.6	10.5	6.8
31	45.0	78	736	2.3	1.6	10.0	6.7
32	107.2	75	736	0.5	0.4	10.2	3.5
33	106.6	75	736	0.7	0.4	9.6	3.6
34	105.6	75	736	0.7	0.4	9.6	3.2
35	105.6	76	736	0.7	0.4	9.5	3.3
36	108.6	76	736	0.7	0.4	9.8	3.2
37	108.0	77	736	0.7	0.4	9.4	3.1
38	26.8	85	733	3.8	1.9	9.5	2.8
39	26.1	87	733	3.8	2.0	10.0	3.0
40	27.0	86	733	3.9	2.1	9.6	3.3
41	27.6	87	733	3.9	2.1	9.7	6.1
42	26.3	88	733	3.7	1.9	9.4	7.1
43	26.6	88	733	3.8	2.1	9.5	2.9
44	28.2	88	733	3.6	2.0	8.8	6.8

TABLE VI - EXPERIMENTAL DATA

LIQUID

No.	Rate	Temp.	Analysis					
			Inlet			Outlet		
		°F	HPh c.c.	M O c.c.	f_o	HPh c.c.	M O c.c.	f_1
1	135	79	20.65	42.22	.021	17.55	42.22	.169
2	131	79	20.65	42.22	.021	17.52	42.22	.170
3	128	79	20.65	42.22	.021	17.25	42.22	.183
4	125	79	20.65	42.22	.021	17.32	42.22	.179
5	126	138	17.30	39.50	.123	14.10	39.50	.276
6	115	138	17.30	39.50	.123	13.50	39.50	.313
7	98	138	17.30	39.50	.123	13.55	39.50	.308
8	97	137	17.30	39.50	.123	12.90	39.50	.343
9	110	120	16.35	39.25	.167	13.20	39.25	.325
10	115	122	16.35	39.25	.167	----	----	----
11	111	122	16.35	39.25	.167	12.80	39.25	.348
12	110	120	16.35	39.25	.167	13.00	39.25	.348
13	115	127	14.30	39.25	.270	11.20	39.25	.429
14	114	126	14.30	39.25	.270	----	----	----
15	113	123	14.30	39.25	.270	12.00	39.25	.388
16	113	122	14.30	39.25	.270	12.00	39.25	.388
17	105	84	13.60	38.80	.299	8.75	38.80	.549
18	102	86	13.60	38.80	.299	10.00	38.80	.485
19	99	84	13.60	38.80	.299	11.00	38.80	.433
20	98	86	13.60	38.80	.299	----	----	----
21	70	87	13.60	38.80	.299	13.85	38.80	.286
22	70	87	13.60	38.80	.299	11.85	38.80	.389

TABLE VI (cont'd)

No.	Rate	Temp.	Analysis					
			Inlet			Outlet		
			HPh	M O	f_o	HPh	M.O	f_1
		°F	c.c.	c.c.		c.c.	c.c.	
23	84	110	14.20	39.75	.264	9.15	39.75	.391
24	83	109	14.20	39.75	.264	8.85	39.75	.399
25	89	108	14.20	39.75	.264	----	----	----
26	87	106	14.20	39.75	.264	8.60	39.75	.405
27	86	106	14.20	39.75	.264	8.50	39.75	.408
28	85	105	14.20	39.75	.264	9.00	39.75	.395
29	89	104	14.20	39.75	.264	9.20	39.75	.390
30	87	104	14.20	39.75	.264	8.95	39.75	.396
31	85	104	14.20	39.75	.264	9.00	39.75	.395
32	49	140	14.80	40.60	.244	9.25	40.60	.380
33	45	136	14.80	40.60	.244	8.90	40.60	.390
34	43	135	14.80	40.60	.244	8.70	40.60	.395
35	42	133	14.80	40.60	.244	8.40	40.60	.402
36	41	131	14.80	40.60	.244	8.45	40.60	.400
37	42	131	14.80	40.60	.244	7.90	40.60	.414
38	89	85	12.50	38.80	.315	2.10	38.80	.582
39	97	87	12.50	38.80	.315	5.50	38.80	.495
40	95	86	12.50	38.80	.315	6.70	38.80	.464
41	92	86	12.50	38.80	.315	7.90	38.80	.433
42	93	88	12.50	38.80	.315	6.50	38.80	.466
43	89	88	12.50	38.80	.315	6.50	38.80	.466
44	88	88	12.50	38.80	.315	5.90	38.80	.485

Specific Gravity of the inert liquid is equal to 1.10

$$CO_2 = 0.0195 \ \frac{\text{lb. mols}}{\text{hr. x sq.ft.}}$$

$$Y = \frac{\%CO_2}{100 - \%CO_2}$$

$$Y_1 = \frac{9.6}{100 - 9.6} = 0.1061; \qquad Y_o = \frac{6.0}{100 - 6.0} = 0.0639$$

From Fig. (17) the area between the operating line and the equilibrium curve at 110° between Y_1 and Y_o is 0.0124 and the driving force $(f_e - f)$ equals

$$\frac{0.0124}{Y_1 - Y_o} = \frac{0.0124}{0.1061 - 0.0639} = 0.294$$

Then when h = 15 ft.

$$K'_L a = \frac{0.0196}{15 \times 2.041 \times 0.294} = 0.00217$$

The values of L, N, $f_e - f$, Y_1, Y_o, $\frac{\text{lb. mols. } CO_2 \text{ absorbed}}{\text{hr. x sq. ft.}}$, and $K'_L a$ are listed in Table VII.

TABLE VII - RESULTS

No.	L	N	$f_c - f$	Y_1	Y_2	lb. mols CO_2 absorbed / hr. x sq. ft.	$K'_2 a$
1	244	2.168	.556	.1265	.0202	.0356	.00197
2	241	2.168	.594	.1013	.0616	.0354	.00183
3	235	2.168	.815	.1265	.0846	.0377	.00142
4	229	2.168	.590	.1039	.0684	.0355	.00185
6	211	2.028	.331	.1362	.0460	.0370	.00368
7	197	2.028	.348	.1493	.0483	.0336	.00304
8	138	2.028	.324	.1362	.0515	.0397	.00403
9	214	2.015	.374	.1363	.0683	.0309	.00274
11	215	2.015	.355	.1401	.0571	.0356	.00333
12	214	2.015	.317	.1300	.0342	.0335	.00350
13	223	2.015	.253	.1038	.0776	.0324	.00425
15	218	2.015	.278	.1137	.0753	.0236	.00281
16	218	2.015	.201	.0707	.0494	.0236	.00388
17	195	2.004	.312	.1237	.0929	.0445	.00474
18	191	2.004	.342	.1173	.0903	.0324	.00314
19	186	2.004	.460	.1187	.0870	.0228	.00212
22	136	2.004	.368	.1073	.0823	.0112	.00407
23	166	2.041	.294	.1061	.0639	.0195	.00217
24	163	2.041	.285	.1111	.0684	.0205	.00235
26	170	2.041	.304	.1200	.0753	.0221	.00239
27	168	2.041	.304	.1137	.0776	.0221	.00241
28	165	2.041	.298	.1025	.0684	.0201	.00220
29	173	2.041	.307	.1111	.0707	.0202	.00215
30	170	2.041	.308	.1172	.0730	.0208	.00220

TABLE VII (cont'd)

No.	L	N	$f_i - f$	Y_1	Y_0	lb. mols. CO_2 absorbed / hr. x sq.ft.	K'_a
31	165	2.041	.279	.1111	.0719	.0201	.00235
32	108	2.085	.213	.1020	.0363	.0140	.00210
33	102	2.085	.193	.1062	.0374	.0140	.00235
34	97	2.085	.185	.1062	.0331	.0139	.00240
35	98	2.085	.204	.1050	.0342	.0155	.00243
36	97	2.085	.206	.1087	.0331	.0148	.00229
37	96	2.085	.194	.1050	.0320	.0155	.00256
38	177	2.004	.170	.1050	.0288	.0303	.00593
39	191	2.004	.229	.1111	.0309	.0314	.00454
40	187	2.004	.243	.1062	.0341	.0254	.00346
41	180	2.004	.297	.1073	.0637	.0195	.00218
42	184	2.004	.289	.1038	.0765	.0254	.00291
43	176	2.004	.236	.1050	.0299	.0242	.00340
44	174	2.004	.276	.0965	.0730	.0269	.00323

CONCLUSION

The results obtained compare favorably with those obtained by other investigators. The coefficient K a obtained experimentally check very well with the values obtained by using the Byrne and Carlson equation mentioned before where

$$K_L' a = 0.000074\ t + 0.0000048\ L - 0.0055$$

In all cases the coefficients are of the same order of magnitude. Any deviations were due mostly to the fact that there was a temperature gradation in the tower when it was operated at raised temperatures. This is caused by heat losses, the tower should be lagged. This was not done because the necessary materials were not at hand.

From the experimental data obtained herein, it can be logically concluded that an absorption of the size described is a suitable piece of equipment for use in a Chemical Engineering Laboratory.

This tower should be operated between 80°and 150°F., the gas velocity ranging from 1 to 4 cu. ft. per min., and the liquid velocity ranging from 1 to 3 lbs. per min. The designed capacity of the tower falls within these limits.